A preliminary feasibility study of potential market applications for non-commercial technology magnets

Michael H. Seversona,*, Ruby T. Nguyena, John Ormerodb, Andriy Palasyukc, Jun Cui

a Critical Materials Institute, Idaho National Laboratory, Idaho Falls, ID 83402, USA
b Critical Materials Institute, John Ormerod Consulting, Loudon, TN 37774, USA
c Critical Materials Institute, Ames Laboratory, Ames, IA 50010, USA

ARTICLE INFO
Keywords:
Permanent magnet
Supply chain
Critical materials
Sustainability
Market substitution
Global electrification

ABSTRACT
Climate change has spurred increased electrification through means of transportation, hydropower, and wind turbines which has caused an increased demand for permanent magnet materials. Current commercial magnet technologies rely heavily on several critical materials such as neodymium, praseodymium, dysprosium, samarium, and cobalt which are primarily sourced and refined outside of the United States (U.S.). To combat these problems, the Critical Materials Institute (CMI) has begun research into alternative magnet compositions to reduce critical material content. Additionally, these alternative magnets can fulfill a gap in the market between high performance neodymium-iron-boron (Nd-Fe-B) and samarium cobalt (Sm–Co) magnets and low performance ferrite or bonded Nd-Fe-B magnets, earning the term gap magnets. This research seeks to compile a simple strategy for identifying an application for these alternative magnets and assessing preliminary market impacts through substitution for two example magnets. The first magnet was identified to be applicable for ancillary motors and sensors in conventional gasoline vehicles with a maximum substitution of 4,825 metric tonnes (mt) per year by the year 2050. The second magnet was identified to be applicable for magnetic couplings in energy and industrial sectors with a maximum substitution of 978 mt per year by the year 2050.

1. Introduction

Electricity generation through wind turbines, hydropower, and solar power are changing the supply chain and the associated required components for efficient energy generation. More specifically, an increase in electric technology requires an increase in permanent magnet quantities to fulfill purposes such as electric motors, generators, speakers, relays, actuators, traveling wave tubes, and many more applications (Arnold Magnetic Technologies, 2020). As subsequent demand increases for permanent magnets, it is important to consider the existing, commercial magnet technologies and their supply chains and the effects of introducing alternative magnet technologies to the market.

Currently, commercial permanent magnets can be separated into five main groups: (1) Sintered/fully dense neodymium-iron-boron (sintered Nd-Fe-B), (2) Bonded neodymium-iron-boron (bonded Nd-Fe-B), (3) Ferrite, (4) Samarium cobalt (Sm–Co), and (5) Aluminum nickel cobalt (alnico) (IMARC, 2020). In order to compare these different groups of magnets and identify the best-suited applications, it is important to understand key magnetic properties. Important magnetic characteristics to consider include maximum energy product ((BH)max), coercivity (Hc), intrinsic coercivity (HcI or Hcj), remanence (Br), and maximum working temperature. This is not an exhaustive list but does provide a general baseline for gauging a magnet's performance. These properties are key to selecting the proper magnet for an application (Arnold Magnetic Technologies, 2020). Additionally, permanent magnets of a particular group come in different grades with different temperature dependent performance characteristics. Typically, a magnet is graded with two independent designations, a number for maximum energy product and a letter(s) for maximum operating temperature. Therefore, it is not only important to consider the magnet type required for an application, but also the magnet grade.

When determining the appropriate magnet for an application, it is also important to consider the economics of each magnet group (Constantinides, 2003). An application does not always require the highest performing magnet due to economic constraints. The most expensive magnet group is typically Sm–Co, followed by Nd-Fe-B, Alnico, and finally ferrite. It should be noted that variance of this order exists due to...
the differing grades of magnets within each category. Of these four, Nd-Fe-B and Sm-Co are the highest performance magnets with correspondingly high (BH)\textsubscript{max} values as shown in Table 1. Additional general magnetic characteristics for a range of magnetic grades can be seen in this table as well. Because of its low costs, the most common magnet group is ferrite which made up 81% of the worldwide volume of consumed permanent magnets in 2019 with a market value of approximately 5.9 billion United States dollars (USD) (IMARC, 2020). In comparison, the world’s largest market value was for Nd-Fe-B magnets at approximately 13 billion USD with a corresponding volume share of 17.9% (IMARC, 2020).

In recent years, there has been an increased focus on fulfilling a gap that exists between the economical, lower performance ferrite magnets and the more expensive, higher performance Nd-Fe-B and Sm-Co magnets as seen in Figure 1. Higher performance magnets rely heavily on critical materials such as rare earth elements (REEs) in their compositions. Concerns exist regarding global supply dependence on China due to approximately 80% of rare earth production coming from this country (Roskill, 2018). Ferrite magnets have already begun adding lanthanum and cobalt to existing compositions to increase their performance (TDK, 2014).

Nd-Fe-B magnets have begun adding cerium in place of neodymium to reduce the consumption of neodymium and simultaneously providing an outlet for more abundant cerium resources (Pathak et al., 2015; Dong et al., 2017) which effectively decreases the remanence, intrinsic coercivity, and maximum energy product (Zhang et al., 2013). Both efforts are evidence of manufacturers attempting to fulfill a gap in the market by providing ‘medium-performance’ magnets. In conjunction with producing alternative magnets to reduce critical material demand, manufacturers have begun focusing on alternative manufacturing methods that allow a reduction in critical material content while maintaining magnetic performance. For instance, in recent years, grain boundary diffusion has become an important topic area for sintered Nd-Fe-B magnets. This manufacturing technique allows manufacturers to use less dysprosium in their composition by strategically enabling dysprosium to be more concentrated at the grain boundary regions of the material (Cui et al., 2022).

CMI has been investigating several new magnet technologies over the years. In this study, two of its magnet technologies were evaluated as alternative magnet technologies to conventional, commercial magnet types. The first magnet selected (hereby referred to as alternative magnet 1) was of lanthanum-neodymium type produced by conventional sintering methods (Parker et al., 2022). Its composition can be seen in Eq. (1). The second magnet selected (hereby referred to as alternative magnet 2) was of cerium-cobalt type and is alloyed with a composition of cerium, cobalt, copper, one or more refractory metals, and optional iron produced by conventional casting methods (Palasyuk et al., 2019). More data on the composition, theoretical magnetic properties, and other details can be found in their respective patent disclosures which can also be found in the Supporting Document (Palasyuk et al., 2019; Parker et al., 2022). Both magnets have undergone a variety of testing and compositional changes with corresponding changes in magnetic properties since their inception. For the purposes of this research, the magnetic properties of the alternative magnets were utilized from the year 2020 and do not reflect the most current magnetic parameters. Our main goal is to propose an analysis methodology to evaluate substitution potentials of alternative magnets, starting from identifying the suitable application based on performance requirement, to quantifying the substituted quantity based on magnet mass, and finally estimating market value and cost savings from substitution.

\[
(La,M_{1-x-y},Nd_{x+y})_{6}Fe_{2}Co_{14}B_{6}
\]

Where:

\[
0.1 \leq x \leq 1
\]
\[
0 \leq y \leq 0.3
\]
\[
0.1 \leq (x + y) < 1
\]
\[
1.9 \leq r \leq 3
\]

Table 1. General magnetic performance of the major commercial magnet technologies and two alternative magnet technologies.

| Magnet Composition                  | (BH)\textsubscript{max} (MGOe) | M\textsubscript{r} (A/m) | H\textsubscript{c} (kOe) | T\textsubscript{m} (Degrees Celsius) |
|-------------------------------------|-------------------------------|--------------------------|--------------------------|-------------------------------------|
| Sintered Nd-Fe-B                    | 25-53                         | 11-14                    | 9-14                     | -0.046 to -0.07                     |
| Sintered Nd-Co                     | 15-25                         | 10-12                    | 9-14                     | -0.02 to -0.04                     |
| Sintered Nd-Fe-Co                  | 10-25                         | 25-30                    | 9-14                     | -0.04 to -0.02                     |
| Sintered Sm-Co                     | 7-12                          | <1                      | <1                       | -0.005 to -0.04                     |
| Sm-Co alloy                        | 4-10                          | 1-3                      | 1-3                      | -0.27 to -0.20                     |
| Alnico                             | 3-5                           | 2-4.6                    | 2-4.6                    | -0.27 to -0.20                     |

Equation 1

\[
(La,M_{1-x-y},Nd_{x+y})_{6}Fe_{2}Co_{14}B_{6}
\]

Where:

\[
0.1 \leq x \leq 1
\]
\[
0 \leq y \leq 0.3
\]
\[
0.1 \leq (x + y) < 1
\]
\[
1.9 \leq r \leq 3
\]

(Parker et al., 2022)
Their magnetic properties can be seen in Table 1 having $(BH)_{max}$ values (18.5–20 MGOe) between the high performance magnets (Nd-Fe-B and Sm-Co, 16–53 MGOe) and the low performance magnets (ferrite, 3–5 MGOe). These two magnet technologies seek to reduce REE consumption by displacing demand from the high performance, REE intensive magnets, predominantly sourced from China.

A literature review, stakeholder outreach, and deterministic market penetration calculation based on magnet substitution was performed on existing commercial magnet technologies to answer several research questions:

1. What applications are feasible for alternative magnets 1 and 2?
2. What are the market impacts of alternative magnets 1 and 2?

The resolution of these questions can provide valuable insight into the potential impact of alternative magnet technologies to enter the market. As additional magnet technologies permeate the market, magnetic applications will have more available options for their design. With increasing complexity in the market, it is necessary to begin providing more simplistic assessment tools that enable the members of the magnet market to perform high level assessments with or without comprehensive magnetic parameter data. Without simple and quick assessment tools such as the work described hereafter, market adoption potential of alternative magnets is reduced as application selection and market impact are largely unknown. The authors hope that this work will provide magnet researchers at low technology readiness levels (TRLs) with a straightforward methodology and framework to perform market assessments to better understand the impact of their technologies. This paper is structured as follows: Section 2.0 provides an overview of current commercial magnet technologies. Section 3.0 details the methodology with results shown in section 4.0. Conclusions can be found in section 5.0.

2. Literature review - overview of commercial magnet technologies

This section provides an overview of commercial magnet technologies regarding magnet market size, common applications for magnets, and other relevant information. This information serves as the rationale and decision framework for selecting an application for a particular magnet. In this study, it was used to assist in the identification of applications for alternative magnet 1 and 2.

2.1. Neodymium magnets

Nd-Fe-B magnets make up the largest share of the permanent magnet market at 66.5% of sales value, including both bonded and sintered Nd-Fe-B magnets (IMARC, 2020). Approximately 90% of total Nd-Fe-B production in the world is dedicated to sintered Nd magnets (Roskill, 2018). Therefore, it can be approximated that 60% of the permanent magnet market consists of sintered Nd magnets and 6.5% consists of bonded Nd magnets.

2.1.1. Sintered neodymium magnets

The first major application of sintered Nd-Fe-B magnet is in traction motors of electric vehicles (EVs). Over 90% of EV traction motors consisted of sintered Nd-Fe-B magnets in their permanent magnet design (Roskill, 2019). This is due to high coercivity, high temperature, and high magnet field parameters possessed by the sintered Nd-Fe-B magnet (Jenkins, 2017). For the same reason that EV traction motors favor sintered Nd-Fe-B magnets, wind turbine generators favor sintered them also (Roskill, 2018). High performance is a requirement for these generators and the reduced weight provided by sintered Nd-Fe-B magnets facilitates design criteria. It is estimated that every 1 MW of direct drive technology for wind turbine capacity consumes 500–700 kg of sintered Nd magnets (Roskill, 2018).

Beyond wind and EV, sintered Nd-Fe-B magnets can be used in applications such as hard disk drives, linear actuators, speakers, microphone assemblies, magnetic separators, DC motors, automotive starters, and servo motors (Arnold Magnetic Technologies, 2020). Unfortunately, outside of hard disk drives where more data are available, these broad categories are not helpful for a quantitative substitution assessment.
2.1.2. Bonded neodymium magnets

Bonded Nd-Fe-B magnets are utilized in applications where small size and unconventional shapes are important. The processing technique of creating bonded Nd-Fe-B magnets involves Nd-Fe-B powder to be combined with a binding agent such as epoxy or nylon (MPCO Magnetic Products, 2020). This allows smaller shapes that do not require subsequent machining of magnets. These characteristics lend the bonded Nd-Fe-B magnet to be heavily utilized in the auto industry, more specifically, small ancillary motors and sensors in a vehicle (D. Torrey, personal communication, Oct. 7, 2020). Technical parameters of a bonded Nd-Fe-B magnet bear resemblance to those of the alternative technology gap magnets as shown in Table 1.

2.2. Samarium cobalt magnets

Sm–Co represented approximately 0.5% of the world market by volume and 2.3% in market value in 2019 (IMARC, 2020). Sm–Co magnets come in two primary types, which depend on the composition of the primary ferromagnetic phase that each type has derived from: SmCo5 and Sm2Co17. The market breakdown between the two compositions favors Sm2Co17 with 85% of the total volume of the Sm–Co market (S. Constantinides, personal communication, Nov. 24, 2020). The performance difference between these two compositions favors Sm2Co17 with increased (BH)max, temperature, and remanence values (Roskill, 2018). Industries tend to favor Sm–Co magnets when high performance requirements, especially high coercivity and high temperature requirements, are needed. This finds military and aerospace applications as likely users of Sm–Co magnets. Additional applications of Sm–Co magnets include traveling wave tubes, electric motors in harsh environments, magnetic couplings, and linear actuators (Arnold Magnetic Technologies, 2020).

2.3. Alnico magnets

Common applications of Alnico magnets include holding magnets, coin acceptors, clutches, bearings, instruments, and guitar pickups, to name a few (Arnold Magnetic Technologies, 2020). Alnico magnets hold the smallest share of the permanent magnet market at 1.8% (IMARC, 2020). Before the invention of rare earth magnets, Alnico magnets were the strongest available permanent magnet (First4Magnets, 2020). Today, Alnico magnets have been largely replaced by their rare earth counterparts due to increased performance characteristics (Osmanbasic, 2020). Alnico is the only magnet that can still operate when temperature exceeds 350 °C.

2.4. Ferrite magnets

Ferrite magnets are the second largest permanent magnet in terms of market size at 29.5% (IMARC, 2020) of the total market in the year 2019. For the same year, the ferrite permanent magnet represents the largest market share in volume at 81% (IMARC, 2020). This is due to ferrite’s excellent performance per cost ratio as seen in Figure 1. Ferrite finds usages in sectors that do not require the high performance characteristics of rare earth magnets (Mughees, 2020). Gap magnets have performance metrics that exceed that of conventional ferrite. However, there appears to be a market for consumers of ferrite magnets seeking an increase in performance as evidenced by ferrite grades containing lanthanum and cobalt to increase performance (Nguyen et al., 2019). Common applications for ferrite magnets include DC permanent magnet motors used in the automobile industry, magnetic separators, switches/relays, medical instruments, and magnetos (Arnold Magnetic Technologies, 2020; Mughees, 2020). The automotive industry has traditionally relied on ferrite magnets for ancillary motors and sensors, however, with the increase in electricification of vehicles, new higher performance magnets are being sought (IMA Magnets, 2017).

3. Methodology

The methodology and calculations to determine a simple alternative magnet technology market penetration can be broken into two segments: (1) identification of an existing, commercial magnet technology for alternative magnet substitution, section 3.1, and (2) the mathematical approach to compare separate magnet technologies and subsequent deterministic market impact calculations based on substitution, section 3.2.

3.1. Identification of an application for alternative magnet substitution

The methodology to determine an appropriate substitution of a commercial magnet technology for an alternative magnet technology was comprised of two components: (1) identification of a commercial magnet with similar performance characteristics to the alternative magnet technology and (2) identification of a suitable application with respect to magnetic performance of the alternative magnet technology. These two components were addressed by a literature review and industry stakeholder correspondence. The literature review, detailed in section 2.0 above, outlines the fundamentals of the major commercial magnet technologies such as market size, magnetic parameters, and applications. Stakeholder correspondence was required to further develop the magnetic properties required of certain applications. A variety of different stakeholders were contacted including national laboratory researchers, expert magnet consultants, magnet industry experts, and electric machine (motors and generators) industry experts. These stakeholder industries were selected to provide a representative view from preliminary magnet research all the way to implementation of magnetic designs in electric machines. To achieve this goal, rather than asking general, standardized questions to the stakeholders, tailored questions were developed that reflected the area of expertise of the stakeholder. For example, electric machine experts were asked about the relationship between magnetic parameters and motor performance, whereas expert magnet consultants were asked about substitution possibilities for gap magnet technologies. A full list of questions can be found in the Supporting Document. The objective of these questions was to build on the information obtained through the literature review to better understand how different magnetic properties and economics correlated with application selection. Communication methods included email exchanges and video teleconference with the participating stakeholders. The results of these correspondences can be found in section 4.0.

3.2. Deterministic market penetration

Market penetration of the two alternative magnet technologies was quantified in two separate market applications, one application for each magnet. The basis of the market penetration was under the assumption that the magnet technologies would be displacing commercial magnets in a specific application. Additionally, it was assumed that redesigning and other related manufacturing capabilities were available to facilitate the substitution. This was performed following the identification of an application outlined by the methodology of section 3.1. Next, the two magnets were analyzed under substitution scenarios from the years 2019–2050 with a magnet deployment year of 2027. A step-by-step guide was provided in the following sections.

3.2.1. Substitution mechanism for magnets

Due to variations in density, maximum energy product, remanence, coercivity, and other physical and magnetic properties, a magnet cannot simply be substituted in an application/device with an equivalent mass. The magnetic performance of the system changes with magnet volume. However, traded magnet quantities and raw materials are reported in mass. For this reason, it is important to have a substitution mechanism in place based on mass. To calculate the mass substitution factor, two methodologies were utilized in this research: (1) an energy product methodology and (2) a flux density methodology. Both methodologies
calculate an output of a magnet performance ratio (MPR) that can be multiplied by the substituted mass to yield the mass of the substituting magnet offering the same magnetic performance.

The energy product methodology operated by first calculating the MPR utilizing maximum energy product and density of the two magnets (Equation 2). Then, dividing both magnet’s energy per unit mass creates a ratio of performance between the two magnets. The equation used to derive MPR can be seen in Equation 3 and Equation 4. By using simple algebra to combine Equation 3 and Equation 4, it is possible to yield an equation that solves for energy in the air gap based on volume of the magnet and magnetic flux density and magnetic field of the magnet. Next, by setting the energy equal to both sides (meaning equal energy stored in airgap), it is possible to cancel the non-changing constant (8π). This creates a system that allows volume of a magnet to be changed to match the energy in the air gap of another magnet.

Magnet Performance Ratio (MPR) = \( \frac{(BH)_{\text{max}} \text{Magnet}_1}{\text{Density Magnet}_1} \) / \( \frac{(BH)_{\text{max}} \text{Magnet}_2}{\text{Density Magnet}_2} \) \[\text{Equation 2}\]

\[E_g = \frac{H_g^2}{8\pi} \times V_g\] \[\text{Equation 3}\]

Where: \( E_g \) = Energy stored in air gap, joule \( V_g \) = Volume of air gap, meter\(^3\) \( H_g \) = Magnetic field of the air gap, \( \frac{\text{Joule}}{\text{Meter}} \)

\[H_g^2 = \frac{B_{g} H_{g} V_{g}}{V_{g}}\] \[\text{Equation 4}\]

Where: \( B_{g} \) = Magnetic field strength, \( \frac{\text{Gauss}}{\text{ampere}} \) \( H_{g} \) = Magnetic field strength, \( \frac{\text{Oersted}}{\text{meter}} \) \( V_{g} \) = Volume of air gap, meter\(^3\)

The flux density methodology also aimed to create a MPR between different magnet technologies, albeit, with a slightly different idea. First, a disc shaped magnet was assumed. Next, the methodology sought to match the magnetic flux density (\( B_r \)) of one magnet with that of another magnet by changing the radius of the magnet required (Equation 5). To do this, an iterative process was used to converge the variables of concern (\( B_r \)) to a selected value. Additionally, the shape of the magnet was dictated by its \( P_c \) value which can be calculated by Equation 6 and Equation 7. By using experimental and known points for magnetic flux density and magnetic field strength of the magnet along the load line at \( (BH)_{\text{max}} \), it is possible to determine \( P_c \) by Eq. (6). Next, Eq. (7) can be used to determine the length to diameter ratio with the calculated \( P_c \) value assuming an open circuit. Lastly, the \( P_c \) can be used to determine the necessary volume of the magnet for the converged \( B_r \) value. Once volume was obtained for the two magnets, a simple conversion to mass using density was performed and the mass ratio of the magnets could be utilized yielding the MPR.

\[B_r = \frac{B_{g}}{2} \left( \frac{L + X}{\sqrt{R^2 + (L + X)^2}} - \frac{X}{\sqrt{R^2 + X^2}} \right)\] \[\text{Equation 5}\]

Where: \( B_{g} \) = Magnetic field strength, \( \frac{\text{Gauss}}{\text{ampere}} \) \( B_r \) = Remanence, \( \frac{\text{Gauss}}{\text{ampere}} \) \( L \) = Length, meter \( X \) = Air gap distance, meter \( R \) = Radius, meter

\[P_c = \frac{B_{\text{max}}}{H_{\text{max}}}\] \[\text{Equation 6}\]

Where: \( B_{\text{max}} \) = Permeance coefficient, unitless \( H_{\text{max}} \) = Magnetic field strength at \( (BH)_{\text{max}} \), Gauss

\[P_c = 1.35 \times \frac{L}{D} \left( \sqrt{1 + \frac{L^2}{D^2}} + \frac{L}{D} \right)\] \[\text{Equation 7}\]

Where: \( D = \text{Diameter, meter} \)

A discussion of the magnet methodology and its relevance to the results of the paper can be found in the discussion, section 4.5. These two methodologies provided a metric (MPR), to be estimated that compared the substitution of the alternative magnet for the current magnet type in a particular application.

3.2.2. Substitution of an existing, commercial magnet for an alternative magnet

A series of stepwise calculations were performed to adequately assess the substitution of an existing magnet technology for an alternative magnet technology. The framework of the methodology can be seen in Figure 2. The first step of the framework involved identifying a potential commercial magnet and application that the magnet was utilized in as outlined in section 3.1. Once identified, the quantity of magnet consumption per year for the application needed to be obtained. Next, a series of substitution curves were created to show the percentage of substitution that would occur over a time series. Additional details regarding the framework can be found in the Supporting Document.

Substitution curves were generated as S-shaped curves that simulate the dynamic process of a new product entering the market and overcoming a competing technology. Traditionally, new technologies face a slower growth period to start, followed by rapid growth, before tapering due to market saturation or product limitations (Hula et al., 2014). This trend is corroborated by examining past automotive technology deployment such as fuel injection, front wheel drive drivetrains, or variable valve timing (Hula et al., 2014). These technology adoptions also showed that it takes approximately 20 years to achieve market saturation for the novel technologies (Hula et al., 2014). The specific substitution curves for both alternative magnet 1 and 2 can be found in the Supporting Document.

These curves were used in conjunction with the calculated MPR (shown in section 3.2.1) in order to determine the quantity of alternative magnet required to fulfill the substitution from an existing magnet technology. Additionally, once the quantity of alternative magnet was calculated, the cost difference between the magnets could be calculated. This was performed by utilizing raw material pricing in conjunction with the composition of each magnet, with the production cost, and production process yields for each magnet. The production costs and production process yields can be found in the Supporting Document. The obtained prices for raw materials can be seen in Table 2 and were obtained from October and November of 2021 (except boron as it is not a commonly traded commodity, so its value was obtained from a United States Geographical Survey value from the year 2020).

Lastly, although it was outside the scope of this effort, a system dynamics model is planned to be developed in a future work to evaluate the impact of the alternative magnet technology to the overall supply chain.

4. Results/discussion

4.1. Correspondence of stakeholder outreach

Seven members of the permanent magnet industry were interviewed which included national laboratories, consulting companies, and
industry partners. These individuals provided valuable insight which can be found in the following sections.

4.1.1. Mechanics of substitution

The easiest type of substitution for magnets of varying compositions is when the magnetic parameters closely align. Direct substitution of one magnet for another magnet is only a possibility if the magnet properties do not change (D. Torrey, personal communication, Oct. 7, 2020). It is likely that any alternative magnet technology will not perfectly align with existing, commercial magnet technologies, thereby requiring additional steps to create an adequate substitution.

Most design processes start with a ferrite magnet, and if the design criteria cannot be met with the performance of ferrite, a bonded Nd-Fe-B magnet is often selected (S. Trout, personal communication, Oct. 7, 2020). This process can be repeated all the way to the highest performing sintered Nd-Fe-B magnets (S. Trout, personal communication, Oct. 7, 2020). However, it was stated that consumers will always try new products to the market, such as gap magnets, as long as price and performance of the new magnets are competitive with the existing magnet technology (S. Trout, personal communication, Oct. 7, 2020).

4.1.2. Electric machines

In the case of magnet substitution in electric machines, redesign was necessary which could include the number of turns in the stator winding and the geometry of the magnetic circuit changing (D. Torrey, personal communication, Oct. 7, 2020). To design a permanent magnet machine with a new magnet, several parameters needed to be considered. The temperature rating is considered first while the magnetic properties are considered second (D. Torrey, personal communication, Oct. 7, 2020). Important magnetic properties include the coercivity and remanence of a magnet when looking at a substitution (T. Raminosoa, personal communication, Oct. 7, 2020). Without the correct coercivity, a direct substitution may lead to demagnetization of the magnet if the new magnet’s coercivity is lower (T. Raminosoa, personal communication, Oct. 7, 2020). Additionally, electrical machines require specific parameters such as operating temperature, torque, current draw, power draw, and heat generation of the machine under load to be considered (T. Raminosoa, personal communication, Oct. 7, 2020). To remedy all these variables in a system, motor designers will utilize finite element modeling (FEM) to determine the motor output and what the effects of different magnets are in the electric machine (J. Herchenroeder, personal communication, Oct. 26, 2020).

Cost is also an important consideration in electric machine magnet selection. In industries such as aerospace, cost can be less important than other industries. Additionally, aerospace often has stringent safety requirements which point towards Sm–Co magnets being a good magnet selection (T. Raminosoa, personal communication, Oct. 7, 2020) with high coercivity and temperature parameters making failure less likely than other magnets (T. Raminosoa, personal communication, Oct. 7, 2020). However, in the automotive industry, cost becomes much more important which is why Nd-Fe-B becomes more prevalent than Sm–Co magnets (T. Raminosoa, personal communication, Oct. 7, 2020).

4.1.3. Gap magnet performance in high maximum energy product applications

For the purposes of this research, high maximum energy product applications are those requiring sintered Nd-Fe-B or Sm–Co series magnets for EV traction motors or wind turbine generators. These high performance magnets allow for smaller sizes which is generally considered more important than the cost of the magnet in the motor (D. Torrey, personal communication, Oct. 7, 2020).

Table 2. Raw material prices used to calculate magnet costs.

| Raw Material          | Price (USD/kg) |
|-----------------------|----------------|
| Cerium metal          | 4.26           |
| Lanthanum metal       | 4.08           |
| Neodymium metal       | 132.76         |
| Copper                | 10.50          |
| Zirconium             | 37.08          |
| Samarium metal        | 13.75          |
| Boron                 | 0.38           |
| Praseodymium metal    | 143.14         |
| Dysprosium metal      | 537.71         |
| Niobium               | 90.75          |
| Cobalt metal          | 26.38          |
| Iron ore              | 0.15           |
| Binding Agent         | 7.42           |
| Strontium Carbonate   | 3.50           |

Figure 2. Framework of methodology for substituting a commercial magnet technology for an alternative magnet technology.
For EVs, a maximum power density is required due to size constraints in the vehicle which requires stronger magnets (T. Raminosoa, personal communication, Oct. 7, 2020). A wind turbine needs a high-power density magnet due to weight requirements (T. Raminosoa, personal communication, Oct. 7, 2020). The construction of a direct drive wind turbine has the permanent magnet generator at the top of the wind turbine tower which creates a weight requirement stipulation for the magnet (T. Raminosoa, personal communication, Oct. 7, 2020). Higher power density magnets require less magnet which means less weight in the wind turbine generator (T. Raminosoa, personal communication, Oct. 7, 2020). Also, it is favorable to select a magnet which favors higher coercivity magnets as they are less likely to demagnetize and fail (T. Raminosoa, personal communication, Oct. 7, 2020).

4.1.4. Gap magnet performance in low maximum energy product applications

Magnet technologies with lower maximum energy products than commercial technologies such as sintered Nd-Fe-B or Sm-Co series magnets have a potential application in the bonded Nd-Fe-B market where gap magnet technologies could be implemented include small brushless DC motors for medical equipment and automotive seat motors, automotive sensors, and tablet/personal computer holding magnets. Additionally, gap magnets could be used in applications where ferrite magnets are currently being used at the edge of their performance limitations such as factory automation applications or appliance motors.

Applications of bonded Nd-Fe-B magnets are seen in significant quantities in the automotive industry (J. Herchenroeder, personal communication, Oct. 26, 2020). Specific applications include tailgate lifts, door slide motors, sun roof motors, torque and angle sensors, battery cooling fans/pumps, speed sensors, electrical power steering system sensors, and water pumps (J. Herchenroeder, personal communication, Oct. 26, 2020). Additionally, these magnets are found in declining applications such as hard disk drive spindle motors and multi-function printers (J. Herchenroeder, personal communication, Oct. 26, 2020). The magnets are found in emerging markets such as internal combustion engine automobile accessory motors and electric vehicle accessory motors (J. Herchenroeder, personal communication, Oct. 26, 2020).

4.2. Implementation of stakeholder engagement and alternative magnet selection

4.2.1. Lessons learned from stakeholder engagement

In relation to electric machines, down selection (identifying magnets that are not a good selection) proved to be an important procedure. Maximum operating temperature of a magnet was the first down selection criteria, as it was the most important characteristic. Alternative magnet 1 possessed a maximum temperature rating of 180 °C which aligned it with similar temperature characteristics of Nd-Fe-B magnets (bonded and sintered). Alternative magnet 2, however, possessed a maximum temperature rating of 180 °C which aligned it with similar temperature characteristics of Nd-Fe-B magnets. Also, it is favorable to select a magnet which favors higher coercivity magnets as they are less likely to demagnetize and fail (T. Raminosoa, personal communication, Oct. 7, 2020).

4.2.2. Selection of application for alternative magnet 1

Based on the literature review and the results of the stakeholder engagement detailed above, the magnet and application for alternative magnet 1 substitution was bonded Nd-Fe-B and automotive ancillary motors and sensors, respectively. The progression of ferrite magnet performance (through lanthanum and cobalt doping) in these automotive ancillary motor and sensors is indicative of an industry looking for more performance but also maintaining lower magnet cost. Currently, ferrite magnets in this application that are on the boundaries of their performance capabilities lead to substitution for bonded Nd-Fe-B to reduce magnet/motor size and increase performance. For this reason, alternative magnet 1 fulfills a gap with its increased energy product compared to bonded Nd-Fe-B while maintaining a lower cost than Nd-Fe-B. Following this logic, two steps are implemented in quantifying the economic impact: 1) estimate the substitution of ferrite magnets to be replaced by bonded Nd-Fe-B magnets and 2) estimate the substitution of bonded Nd-Fe-B to be replaced by alternative magnet 1. In other words, under this scenario, ferrite, bonded Nd-Fe-B, and alternative magnet 1 co-exist in the ancillary motor application.

4.2.3. Selection of application for alternative magnet 2

Based on the literature review and the results of the stakeholder engagement detailed above, the magnet and application for alternative magnet 2 substitution was Sm2Co17 and magnetic couplings in industrial and energy applications, respectively. The Sm2Co17 magnet was selected for substitution due to similar magnetic performance characteristics as evidenced by Table 1. The key characteristic of similarity was both magnets' ability to operate at high temperatures. Magnetic couplings were chosen as the application due to alternative magnet 2's high remanence value and low temperature coefficients for remanence and coercivity at -0.06 %/°C and -0.13 %/°C, respectively. This translates into good performance for a magnetic coupling which relies on remanence to deliver adequate torque in the coupling (Quadrant, 2016). With temperature coefficients close to zero, the magnet also provides consistent performance across a range of temperatures. Lastly, it was determined that through additional FEM and design considerations, lower coercivity magnets could still be utilized (Flight Works, 2016; Quadrant, 2016). This mechanism was determined to be a single step in which Sm2Co17 magnets were substituted for alternative magnet 2.

4.3. Substitution of bonded Nd-Fe-B in automotive ancillary motor and sensor applications

Table 3 shows quantity of ferrite magnets in conventional gasoline vehicles (cars and light trucks) computed from vehicle sales data for the United States from the Energy Information Administration (EIA) (EIA, 2020) and ferrite magnet mass in vehicles (Nguyen et al., 2019). A low and a high range for ferrite magnet consumption was calculated due to the variance in quantity of ferrite magnet contained within conventional gasoline vehicles which ranged from 750 to 1,601 g for cars and 2,208 to 3,525 g for light trucks (Nguyen et al., 2019). The cumulative, calculated ferrite consumption from years 2019–2050 was 620,103 and 1,076,152 mt of ferrite magnet for the low and high range, respectively.

Next, an MPR to compare ferrite and bonded Nd-Fe-B calculated by Eq. (2) yielded a value of 0.42 meaning that only 0.42 kg of bonded Nd-Fe-B would be required to substitute for 1 kg of ferrite. This MPR in conjunction with the substitution curves for ferrite to bonded Nd-Fe-B (Supporting Document) yielded a low range of approximately 1,335 mt and a high range of approximately 9,358 mt of bonded Nd-Fe-B by the year 2050 to be substituted for ferrite magnets.

Subsequently, an MPR to compare bonded Nd-Fe-B and alternative magnet 1 calculated by Eq. (2) yielded a value of 0.74 meaning that only 0.74 kg of alternative magnet 1 would be required to substitute for 1 kg of...
bonded Nd-Fe-B. This MPR in conjunction with an S-shaped substitution curve for bonded Nd-Fe-B to alternative magnet 1 (Supporting Document) yielded the total substitution of alternative magnet 1 for bonded Nd-Fe-B is shown in Figure 3. The lowest quantity of alternative magnet 1 required was approximately 688 mt in the year 2050 whereas the highest quantity of alternative magnet 1 required was approximately 4,825 mt in the year 2050. Validation of these substituted values was performed by comparing the calculated forecast with a literature forecast for bonded Nd-Fe-B in 2030 as this is typically the farthest that forecasts are conducted. By 2030, total bonded Nd-Fe-B demand for all applications was projected to be 35,000 mt (Benecki et al., 2020) indicating that the calculated bonded Nd-Fe-B magnet projection range for automotive ancillary motors and sensors of 1,300 to 9,100 mt (~3–26% of the total bonded Nd-Fe-B market) was a reasonable estimation.

Next, the total cost savings or cost increase of substitution could be calculated from the quantity of substitution. As seen in Figure 3, the substitution of alternative magnet 1 from bonded Nd-Fe-B resulted in dramatic cost savings in the automotive ancillary motors and sensors application. The highest total cost savings was approximately 161 million USD per year by 2050, and the lowest total cost savings was approximately 23 million USD per year by 2050. The cost savings of substitution for alternative magnet 1 can be attributed to: (1) the reduction of magnet mass required to provide similar performance to bonded Nd-Fe-B magnets and (2) the reduction of rare earth content such as neodymium in the alternative magnet.

Substitution of Samarium Cobalt in Magnetic Couplings for Industrial and Energy Applications.

As detailed in section 4.2.3, Sm2Co17 in magnetic couplings for industrial and energy applications was selected as the magnet and application for substitution, respectively. Unfortunately, public consumption data for Sm2Co17 in this application was not readily available. Therefore, consumption in magnetic couplings for industrial and energy applications was obtained from magnet industry consultants. Next, an MPR calculated by Eq. (2) yielded a value of 1.41 meaning that 1.41 kg of alternative magnet 2 would be required to substitute for 1 kg of Sm2Co17 magnet. Despite the nearly 40% increase in magnet mass required for this application, magnetic couplings were still deemed an appropriate substitution due to perceived flexibility of magnetic coupling design. Without stringent system size and weight specifications, an increase in magnet mass would be of minimal importance. The results showed that by the year 2050, a range of approximately 244 mt at the low end to 978 mt at the high end of alternative magnet 2 were consumed. Validation of these substituted values was performed by comparing the calculated forecast with a market forecast for Sm–Co in 2030. By 2030, total Sm–Co demand for all applications was projected to be 5,000 mt (Benecki et al., 2020) indicating that the estimated Sm–Co magnet projection of 700 mt

| Year | Gasoline Car Vehicle Sales (Thousands) | Low Range Total Ferrite Magnet Mass per Year (mt) | High Range Total Ferrite Magnet Mass per Year (mt) | Gasoline Light Trucks Vehicle Sales (Thousands) | Low Range Total Ferrite Magnet Mass per Year (mt) | High Range Total Ferrite Magnet Mass per Year (mt) |
|------|---------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 2019 | 6,710                                 | 5,033                                         | 10,743                                        | 2019                                          | 7,255                                         | 16,019                                        |
| 2020 | 6,572                                 | 4,929                                         | 10,522                                        | 2020                                          | 7,162                                         | 15,814                                        |
| 2021 | 6,328                                 | 4,746                                         | 10,131                                        | 2021                                          | 7,198                                         | 15,894                                        |
|      | ...                                   | ...                                           | ...                                           |                                               | ...                                           | ...                                           |
| 2047 | 7,072                                 | 5,304                                         | 11,322                                        | 2047                                          | 5,919                                         | 13,069                                        |
| 2048 | 7,101                                 | 5,326                                         | 11,369                                        | 2048                                          | 5,905                                         | 13,038                                        |
| 2049 | 7,109                                 | 5,332                                         | 11,381                                        | 2049                                          | 5,894                                         | 13,013                                        |
| 2050 | 7,121                                 | 5,341                                         | 11,400                                        | 2050                                          | 5,892                                         | 13,009                                        |
| Total| 213,493                                | 160,119                                       | 341,802                                       | Total                                         | 208,326                                       | 459,984                                       |

Figure 3. Quantity of alternative magnet 1 substituted for bonded Nd-Fe-B and cost savings of substituting for alternative magnet 1 under a low range and high range scenario.
for magnetic couplings in 2030 (~14% of the total Sm-Co market) was a reasonable estimation.

Next, the total cost savings or cost increase of substitution could be calculated from the quantity of substitution. As seen in Figure 4, the substitution of Sm$_2$Co$_{17}$ for alternative magnet 2 in magnetic couplings for energy and industrial applications showed a high cost savings of approximately 8.1 million USD per year by 2050, and the lowest total cost savings was approximately 2 million USD per year by 2050. This cost savings was largely due to the decreased production cost of alternative magnet 2 production versus Sm$_2$Co$_{17}$ with a smaller contribution attributed to reduction of raw material costs.

4.4. Selection of MPR methodology

As outlined in the methodology in section 3.2.1, two approaches could be taken to develop an MPR to calculate the amount of magnet required to match the performance of another magnet. The methodology used in the results section was the energy product methodology which was utilized based on the rationale provided below.

When comparing alternative magnet 1 and bonded Nd-Fe-B, the energy product methodology produced an MPR of 0.74, whereas the flux density methodology produced a value of 0.55. Additionally, when comparing alternative magnet 2 and Sm$_2$Co$_{17}$, the energy product methodology produced an MPR of 1.41, whereas the flux density methodology produced a value of 1.39. Variations between the two methodologies are attributed to the parameters of analysis when making the comparison (i.e., energy product or flux density). For instance, when examining Sm$_2$Co$_{17}$ and alternative magnet 2 in Table 1, there is not a significant difference between both remanence and maximum energy product for the two magnets. However, bonded Nd-Fe-B and alternative magnet 1 see larger differences between remanence and maximum energy product. The differences between the respective magnetic parameters are what contribute to the unequal results between methodologies. Another reason for greater difference between the two methodologies for bonded Nd-Fe-B and alternative magnet 1 lies with the non-linear normal demagnetization curve of alternative magnet 1. All other magnet technologies in this analysis possessed linear normal demagnetization curves which was the basis for the flux density methodology. This led to the selection of the energy product methodology because it is a more encompassing magnetic variable which incorporates the flux density and coercivity of a magnet into its parameter, providing a more comprehensive view of magnetic performance. Additionally, the energy product methodology was much simpler than the flux density methodology which is more in line with the scope of the research of developing a straightforward, replicable process for others to assess a magnet’s preliminary market feasibility.

4.5. Limitations and shortcomings

Several limitations exist for the execution of this research. First, even though substitution was calculated over a projected period of time, market prices for commodities and production costs for magnets remained static. This is an unlikely scenario and does not provide an accurate representation of the system as it progresses dynamically through time. However, without a more intensive simulation model, static prices were the best approximation that could be utilized. A further explanation of the importance of raw commodity prices can be seen in Figure 5 which shows the difference in magnet cost based on cobalt prices. Accounted for in the figure are the magnet compositions, production costs, production process yields, and MPR for alternative magnet 2. Along the same line, demand for end products (e.g., vehicle sale projections and magnetic coupling demand) were computed as static, whereas the actual demand in the system would respond to disturbances dynamically with reduction or increases in demand.

The next limitation of the research builds off the previous limitation. The substitution mechanism was deterministically driven by assumed substitution curves (ferrite to bonded Nd-Fe-B, bonded Nd-Fe-B to alternative magnet, etc.). In reality, a substitution mechanism would dynamically look at the economic favorability of a new magnet technology in order to make a determination on favorable substitution. However, this was outside the scope of the current work as it would require a more intensive simulation model. Additionally, this market substitution could prove to be one of the largest challenges for the successful deployment of the alternative magnets as up seating incumbent technologies is dependent on application design.

The final limitation dealt with the assumption that alternative magnets could be substituted based on only magnetic characteristics and by a singular characteristic. While an excellent indicator of magnetic performance ($B_H$)$_{max}$ and flux density do not account for the physical properties that a magnet may require to be suitable for a particular application.

Figure 4. Quantity of alternative magnet 2 substituted for Sm$_2$Co$_{17}$ in magnetic couplings and cost savings substituting for alternative magnet 2 under a low range and high range scenario.
(i.e., tensile strength, thermal conductivity, etc.). These physical characteristics vary from magnet to magnet, and each application has a different minimum requirement for specific characteristics. For instance, another CMI project successfully demonstrated its ability to reduce the brittleness of Sm–Co magnets improving the magnet’s range of potential applications (Ames Laboratory, 2021). Application limitations due to brittleness included environments with too much vibration or mechanical shock (Ames Laboratory, 2021). It should be noted that magnet selection is a process of nuance with a plethora of decision factors making 100% certainty of application adequacy for the authors difficult. Additionally, creating an MPR based on a singular magnetic characteristic may not yield the exact quantity of alternative magnet required for a particular application. Many application designers such as electric machine designers utilize FEM for exact measurements and system design, however, this detailed approach would be impractical for a preliminary feasibility assessment (Integrated Magnetics, 2021).

4.6. Next steps and future work

To address some of the listed limitations, our future work involves creating a system dynamics model to evaluate the alternative magnet substitution impact to the material supply chain. This future work would build on the foundational work established by this research in evaluating how to compare different magnets of varying compositions, magnetic performance, and physical characteristics.

Additionally, the future work would address some of the limitations and shortcomings of the current work by providing a dynamic substitution mechanism that evaluates substitution based on current market prices of different rare earth commodities. This is a more realistic representation of the actual market system than calculating substitution based on static, market prices for these commodities. Because market prices would change dynamically, the substitution mechanism therefore would also be dynamic.

5. Conclusion

This research showed a comprehensive approach to selecting a new application for an alternative magnet technology and determining the quantity of an alternative magnet by deterministic substitution. This was performed by analyzing the literature, engaging stakeholders participating in the magnet industry, and making determinations based on magnetic performance and application requirements. Additionally, the research presented two methods of substitution: the energy product methodology and the flux density methodology. Both approaches provide adequate rationale for a preliminary estimate of the required magnet mass for substitution. The results of the energy product methodology showed a maximum of 4,825 mt of alternative magnet substitution in 2050 by switching to alternative magnet 1 from bonded Nd-Fe-B in the highest substitution scenario. The cost savings of this substitution yielded a result of 161 million USD in 2050. The analysis of substitution for Sm–Co magnets for an alternative magnet showed a substitution mass of 978 mt of alternative magnet 2 in 2050 in the highest substitution scenario. This equated to a cost savings of 8.1 million USD in 2050. Overall, this research provides important considerations and results to determining future magnet substitutions in response to a growing electrified world and growing supply chain concerns for rare earth magnets.

Declarations

Author contribution statement

Mike Severson; Ruby T. Nguyen: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

John Ormerod: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Andriy Palasyuk; Jun Cui: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Funding statement

Ruby T. Nguyen was supported by the Advanced Manufacturing Office [AL-12-350-001].

Data availability statement

Data included in article/supp. material/referenced in article.
Declaration of interests statement

The authors declare the following conflict of interests: The authors declare patents US20220076867A1 and US20190185980A1, invented by Jun Cui and Andriy Palasyuk, as related to this work.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2022.e11773.

References

Alibaba, 2021. Impeccable polyphenylene sulfide price selections for utmost accuracy - Alibaba.com. Retrieved 4 Nov. 2021. https://www.alibaba.com/showroom/polyphenylene-sulfide-price.html.

ArgusMedia, 2022. Argus metal prices. Retrieved 20 June 2022., http://www.argusmedia.com/metals/argus-metal-prices/.

Arnold Magnetic Technologies, 2015. Understanding permanent magnets. TECHNotes TN 9802 (rev.2018a), 1-5. Retrieved 6 July 2021.

Arnold Magnetic Technologies, 2020. Permanent Magnet Applications Guide Arnold Magnetic Technologies. Arnold Magnetic Technologies, p. 1.

Benecki, W.T., Constantinides, S., Ormerod, J., Trout, S.R., 2020. The Global Permanent Magnet Industry 2020-2030, 1. Self published, pp. 80-125.

Constantinides, S., 2003. Magnet selection. Retrieved 12 Oct. 2021.https://www.arnoldmagnetics.com/wp-content/uploads/2017/10/Magnet-Selection-Constantinides-Go rham-2003-psn-bi-res.pdf.

Constantinides, S., 2009. Understanding and using reversible temperature coefficients. Retrieved 3 Oct. 2022. https://www.arnoldmagnetics.com/wp-content/uploads/2017/10/Understanding-and-Using-Reversible-Temperature-Coefficients-Constantini des-Magnetics-2010-psn-bi-res.pdf.

Cui, J., Ormerod, J., Parker, D., Sales, B.C., Conner, B.S., Pandey, T., Palasyuk, A., Cui, J., 2022. crunchy magnets. Advanced Materials 27 (16), 2663 – 2667.

Dong, S., Li, W., Chen, H., Han, R., 2017. The status of Chinese permanent magnet industry and R&D activities. AIP Advances 7 (5), 056237.

EIA, 2020. Annual energy outlook. Retrieved 6 August 2020. https://www.eia.gov/outlooks/aeo/.

EIA, 2021. Magnetic circuit design. Retrieved Dec. 13, 2021. https://www.mpcomagnetics.com/bonded-ndfeb/.

Flight Works, I., 2016. Sealed direct drive or magnetic drive: a comparison of technologies and suitable use. Retrieved 26 Oct. 2021. https://www.flightworksin c.com/wp-content/uploads/White-Paper-Sealed-Direct-Drive-or-Magnetic-Drive-A-Comparison-of-Technologies-and-Suitable-Use.pdf.

Hula, A., Alson, J., Bunker, A., Bolon, K., 2014. Analysis of Technology Adoption Rates in New Vehicles. SAE Technical Paper, 11.

IMA Magnets. 2017. The increased use of magnets in the automotive industry - Blog - IMA. 2020. https://www.imamagnets.com/en/blog/the-increased-use-of-magnets-in-the-automotive-industry/.

IMARC, 2020. Magnet Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2020-2025, 13-16.

IMC, 2019. Bonded magnets supplier - magnets - MPCO magnetics, 2020, from https://www.mpcmagnetics.com/bonded-ndfeb/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design -guide,Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.

IMARC, 2021. Permanent Magnets Design Guide | Magnetics Design Guidelines. Retrieved 6 July 2021, from https://www.imamagnets.com/magnet-design-guide/Jenkins, 2017 Jenkins, J., 2017. Magnetic Torque Coupling Design. Retrieved 13 Oct. 2021, from https://www.imamagnets.com/tudom-magnetic-design-modeling/.