# Permanent Magnets in a Changing World Market

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Magnetics Business and Technology, Spring 2016, Page 6-9

**Abstract:** There are several commercially available permanent magnets. In sequence of invention they are: alnico, ferrite, SmCo (samarium cobalt), NdFeB (neodymium iron boron, Neo), and SmFeN (samarium iron nitride). The last three types are considered "rare earth" magnets because they contain one or more rare earth elements. In terms of total quantity produced each year the permanent magnet market is dominated by the ferrite and rare earth types. Approximately 70 weight percent of ferrite and rare earth permanent magnets are utilized in motors. Permanent magnet motors have several advantages over induction (non-magnet) types, the most notable being efficiency. This coupled with the pervasive use of motors means that permanent magnets are a key enabling material in modern economies.

Author's note: By October 2019 actual and forecast output of REO globally and especially in China has changed significantly since the writing of this paper in early 2016. If the reader is interested, visit the Publications page on www.MagMatLLC.com for more recent publications and the USGS website for rare earth statistics at: https://www.usgs.gov/centers/nmic/rare-earths-statistics-and-information.

## Magnet Alternatives

The 20th century saw remarkable developments in the area of permanent magnet materials. Approximately each 12 years a new and significantly improved magnet material was invented. The first major invention was for the alnico family of magnetic materials commencing in late 1931 with continued development through 1975. Then in 1952 a magnetic ceramic was marketed by Philips[1]. The material is today referred to as a permanent magnet ferrite, a hard ferrite or, simply, ferrite magnet. The composition is represented by $MO \bullet (Fe_2O_3)_6$ where the metal M can be barium, lead or strontium. Almost all ferrite magnets are today made using strontium because of environmental and safety issues associated with both barium and lead. The development of ferrite magnets overlapped the end of the alnico development period. (Note there are soft magnetic ferrites based on manganese, nickel and/or zinc and these should not be confused with the permanent magnet ferrites).

Starting in the 1950s researchers worked with rare earth elements, notably yttrium, in combination with the naturally ferromagnetic elements iron, nickel and cobalt. Yttrium cobalt ($YCo_5$) was found to have interesting magnetic properties. Continuing research on the family of REE+(Co,Fe) resulted in the discovery in1965 of $SmCo_5$ by Karl Strnat at Wright Patterson AFB in Ohio, USA. Dr. Strnat relocated to the nearby University of Dayton Research Institute and along with Herb Mildrum and Al Ray continued development of SmCo[2]. As with much research, numerous laboratories were exploring similar compositions and assignment of the discovery is often based on who received the patent or first published the data.

A part of the metallurgical research was a hunt for stable alloys of samarium and cobalt with reduced rare earth content. The result was $Sm_2Co_{17}$. This alloy, while promising, had insufficient coercivity (resistance to demagnetization) resulting in inferior maximum energy product. After numerous trials, the team of Strnat/Ray/Mildrum arrived at additions of copper and a refractory metal, preferably zirconium, to optimize residual magnetic induction (Br), maximum energy product and coercivity[2]. This enhanced $Sm_2(Co,Fe,Cu,Zr)_{17}$ alloy, also referred to as SmCo 2:17, was commercialized by 1975 and immediately became the material of choice for demanding applications.

By 1978, SmCo 2:17 was widely utilized in high performance motors and in sensors in hostile ambient conditions such as automotive under-the-hood applications. Civil unrest in Zaire (Belgium Congo) in 1978 disrupted the supply of cobalt and the price of cobalt increased 6.5x over the base. As a result the search for a cobalt-free high performance magnet began in earnest. Many laboratories were experimenting with rare earth elements and iron but these alloys resulted in poor permanent magnet properties though some had promising *soft* magnetic properties. N.C. Koon, along with B.N. Das and others at the Naval Research Laboratory, was attempting to develop an ultra-high performance soft magnetic material. As part of an attempt to prevent crystallization during melt-spinning the misch metal-iron alloy, the glass-forming element boron was added to the composition[3,5,6]. The surprising result was a moderately high performance permanent magnet material for which the Navy filed for and received composition, process and product patents[4]. In the fall of 1980, Koon reported on this discovery and shortly thereafter both Musato Sagawa (Sumitomo) and John Croat (GM) optimized the composition and processes for Neo (NdFeB) magnets[7]. Competitively, NdFeB was reputed to have been identified by Kus'ma and coworkers in the USSR in the late 1970s. The first commercial product was reportedly sold by Crucible Magnetics (Elizabethtown, KY USA) in November 1984.

The commercialization of NdFeB did not stop research for other high performance magnetic materials. In Europe the Concerted European Action on Magnets (CEAM) ended up influencing the discovery of nitride magnets, specifically SmFeN, by J.M.D. Coey at Trinity College. With a maximum energy product of ~40 MGOe, this alloy had the potential of a major invention. While important, the limitation is that the material is formed as a powder and decomposes above ~450 °C preventing consolidation to full density and limiting its use to bonded magnet applications. Due to the dilution effect of the binder, maximum energy products achieved in commercial bonded magnet products are below 20 MGOe.

Thus there are currently two major commercial materials (ferrite and NdFeB) and three lesser used materials (alnico, SmCo and SmFeN).

**Key parameters**

There is a long list of magnet characteristics to consider for use in an application. Among the more important is the temperature of use. As one might imagine, the magnetic field is not constant – it changes with temperature, getting either stronger or weaker. Figure 1 shows the usable temperature range for each of the materials. Conveniently, most applications utilize magnets between -40 and +150 °C and all listed materials are usable.

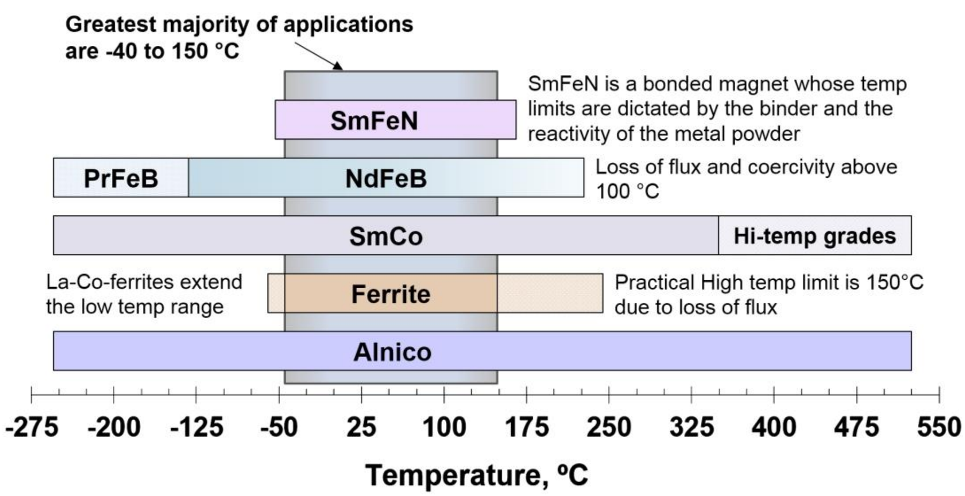


**Figure 1.** Acceptable Magnet Use Temperatures

Issues of raw material price and availability are at the core of today's discussion and are influenced by the general availability of the raw materials, geographic distribution, ease of recovery from mined ore, and open market trading. Of the 120+ actual and theorized elements, only 36 are potentially useful to form a magnetic material and only a few can actually produce a magnetic output, the source of which is electron spin imbalance. A list of these elements reveals that most, individually and in combinations, have already been exhaustively investigated over a period of at least 150 years[10]. Elements in bold greed in Table 1 are readily available; non-bold green are also very available; black text indicates possible minor problems with pricing or supply; red letters indicate rare or problematic elements.

**Table 1.** Elements suitable for making magnetic materials

| | Constituents | |
|---|---|---|
| | **Major** | **Minor** |
| **Soft Magnetic Materials** | | |
| Iron | Fe | |
| Silicon Steel | Fe | Si |
| Nickel-Iron | Fe Ni | |
| Moly Permalloy | Ni Fe | Mo |
| Iron-Cobalt | Fe Co | V |
| Soft Ferrite | Fe Mn Ni Zn | O |
| Metallic Glasses | Fe Co Ni | B Si P |
| **Permanent Magnets** | | |
| Co-Steels | Fe Co | |
| Alnico | Fe Ni Co Al Cu | Ti Si |
| Platinum Cobalt | Pt Co | |
| Hard Ferrites | Fe Sr | |
| SmCo | Co Sm Gd Fe Cu Zr | |
| Neodymium-iron-boron | Fe Nd Dy (Y) B Co | Cu Ga Al Nb |
| Cerium-iron-boron | Fe Nd Ce B | |
| SmFeN | Fe Sm N | |
| | | |
| MnBi | Mn Bi | |
| MnAl(C) | Mn Al | Cu C |

Of all the elements used in magnetic materials, rare earth elements are the most problematic based on geographic limitations on sourcing. China still produces 90% of the rare earth oxides used each year. China also produces (and consumes) over 80% of all permanent magnets. There is inconsequential production of NdFeB in the USA. When a US-based company wishes to purchase NdFeB, the magnets are imported. The US ITC maintains statistics[11] for importation of "metal magnets" which include NdFeB, SmCo, FeCrCo, Vicalloy and similar permanent and semi-hard magnetic materials. The great majority of import value is represented by NdFeB. Imports into the USA for 2015 totaled $274 million. If 85%, probably a reasonable estimate, were NdFeB, that's $233 million - less than 3% of the global NdFeB market. Of course much of the magnet import occurs with magnets already inside products and these are not counted as magnets for import statistics.

## Shifting Markets

Over 20 applications for rare earth magnets have been identified. Many of them are undergoing dramatic change – either growing in use of RE magnets or shrinking. Six of those markets will be discussed below.

### 1) HDDs

One of the oldest uses for rare earth magnets has been in hard disk drives (HDDs). One magnet, a compression bonded NdFeB magnet, is used in the spindle drive motor to spin the platter. Because the platter is not expected to spin-up quickly, lower strength compression bonded magnets can be used. The second magnet is utilized in the voice coil motor (VCM). It provides a static magnetic field against which an electromagnetic coil acts to move the read-write head. This action must be very fast therefore strong NdFeB sintered magnets are used. To protect the magnet from corrosion and release of particulates from the magnet, both the magnet and the soft alloy flux return path are nickel plated.

In 1990, it was reported that HDDs consumed over 70% of all NdFeB. In 2015, magnet usage is estimated to have been 7,500 tonnes. Competing forecasts have the HDD market either recovering to consume over 20,000 tonnes by 2020 or dropping to 6,000 tonnes. What happens is largely dependent upon price and performance of SSDs (solid state drives), a disruptive and competing technology. My personal forecast leans toward the low estimate of NdFeB consumption.

### 2) Hybrid Electric Cars and Trucks

This is a growing market, though not as quickly as forecast even a few years ago. Regions experiencing pollution are likely to see government mandates regarding implementation of more environmentally friendly electric drive systems. High gasoline prices will also drive users to purchase EVs (electric vehicles). But the rate of growth has been temporarily slowed with USA sales for 2015 of EVs, PHEVs, and BEVs totaling 499,667 or 2.89 of total car and small truck sales. In addition to the traction drive motor that provides motive force, vehicles are becoming more electrified using motors for electric power steering and electric braking. Some vehicles are using stop/start technology wherein a single device functions both as the alternator and a starting motor – a motor strong enough to initiate vehicle motion while the engine re-starts[12]. Consumption of rare earth magnets in transportation is estimated at 7,000 tonnes for 2015 rising to 17,000 tonnes in 2020.

**3) Wind Turbines**

The two fastest growing means of producing electricity are wind and solar. Wind power generation uses generators and while most of these have been the induction type, an increasing number are of the direct drive or hybrid drive type. Direct drive permanent magnet generators of wind power are more energy efficient – able to produce more power output with slower wind speeds. Direct drive also eliminates the major cause of maintenance and repair – the gearbox. Tower power output is a function of the propeller swept area and wind velocity. Propellers are limited in size by material strength which also limits maximum rotational speed. Current commercial scale tower propellers turn at 10 to 12 rpm. Induction generators must spin at high rpm, e.g. 1800 rpm. The speed change is accomplished using a 3-speed gearbox. Torque and shaft distortion, even of the elastic type, causes gear wear and noise.

Redesign to use a permanent magnet generator (PM generator) requires a larger diameter rotor/stator and large quantities of magnets, but eliminates the gearbox (direct drive generator) or reduces the gearbox to 2-stage in a hybrid drive, medium speed geared PM generator with a reduced magnet requirement. Magnet usage is about 600+ kg per MW output on older towers up to 4 MW. Newer towers use ~500 kg per MW for generators of 5+ MW. Medium speed geared PM generators use about 200 kg per MW.

In addition to numerous new stories about the wind power industry, several organizations produce industry statistics, including: Global Wind Energy Council (GWEC), the American Wind Energy Association (AWEA), The European Wind Energy Association (EWEA), the World Wind Energy Association (WWEA), International Energy Agency (IEA Wind), and the Chinese Wind Energy Association (CWEA).

Consumption in 2015 was 8,500 tonnes of NdFeB magnets. This annual quantity is expected to grow slightly until the mid-2020s when it will peak and then slowly decline.

**4) Electric Bikes**

This is a stealth application – one that grew rapidly without much notice, at least in the west, until it was a large market. In 2009, the China market for EBs (electric bikes) was 20 million units. The major market is currently China and Southeast Asia, but India's market is growing and global production in 2018 is forecast to be 60 million units. Magnet consumption per bike is highly variable ranging from motor assisted pedaled bicycles to high-power sport bikes competing with conventional motorcycles. Magnet usage in 2015 was 6,000 tonnes and is expected to rise to over 15,000 tonnes annually by 2018.

**5) Air Conditioning**

Air conditioners typically have three-to-four motors. One drives the compressor pump. A second pumps the cooling fluid from the condenser to the chiller. Another motor pushes air through the heat exchanger fins at the compressor end. Another motor moves air through the chiller fins and circulates cool air into the room to be air conditioned. Most of these motors are now NdFeB. The largest and growing market for air conditioning is in China, Southeast Asia, and India. Demand is for homes, businesses and factories. Precise market size has not yet been well-quantified but is estimated for 2014 at over 4,000 tonnes of NdFeB, a number that is likely to grow.

**6) Acoustic transducers**

A common name for these devices is "speakers". They come in all sizes and shapes. For example, more than 6.8 billion cell phones are currently connected. Most phones have at least one speaker and a vibrator motor – they use NdFeB. Many smart phones are supplied with earbuds which use NdFeB. Other major speaker uses are in transportation. Automobiles use 2, 4 or more speakers, the majority of which use NdFeB magnets. The global market for cars and small trucks is over 70 million units per year – times four = 280 million speakers using NdFeB. The market in 2015 is estimated to be over 4,500 tonnes and growing slowly.

## The forecast

Every forecast starts with known data and extrapolates into the future. A problem we have has been a disjoint between published figures of REO (rare earth oxide) production and the quantity of rare earth magnets produced – a problem with the "known data". With 80% of magnets being produced within China by several hundred companies, accurately tracking magnet production is difficult. However, estimates can be made.

With 90% of the REO production in China, one might expect even more difficulty quantifying production. The Chinese government has production quotas and tracks production, periodically publishing output. However, a problem exists due to production and sale of REO on the black market. Published production data for REO can be compared with probable magnet output and the gap then indicates the size of the REO black market.

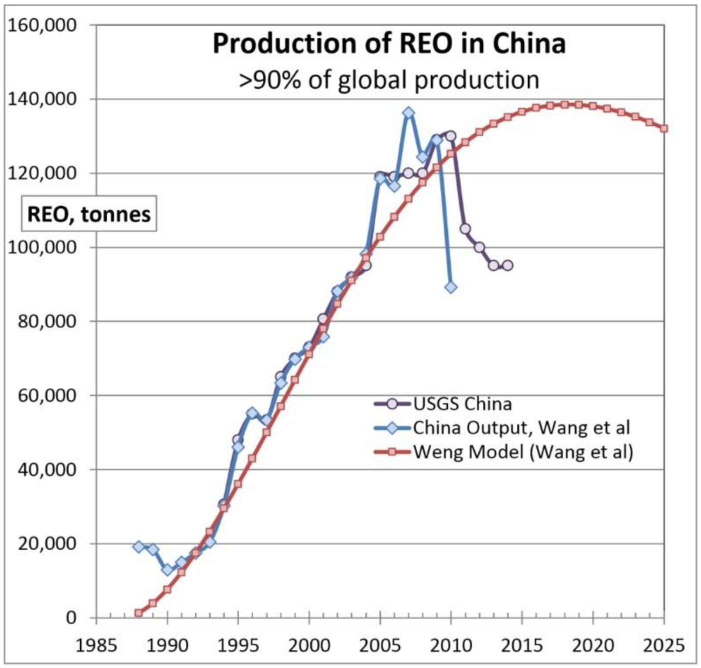


**Figure 2**. Production of Rare Earth Oxide in China

Let's start with existing data and a forecast of future REO production based on the Weng model for production of an exhaustible resource – see Figure 2. Production data is provided in the reference paper describing application of the Weng model to REOs[13] and from the USGS[14]. Data is for China production only. The data and chart show a significant drop in production starting in 2011 and continuing through 2014. Published data coincides closely with Chinese production quotas for REO and consists of all three main types of ore bodies.

The red line in Figure 2 is the Weng model output and shows a peaking of production in 2018-2019. The model is easily affected by several issues including: changes in government quotas, discovery of new resources, disruptive changes in technology either consuming more or less than at the present, government mandate regarding use of the resource (e.g., EVs or CAFÉ standards), rate of consumption based on general economic situations, etc.

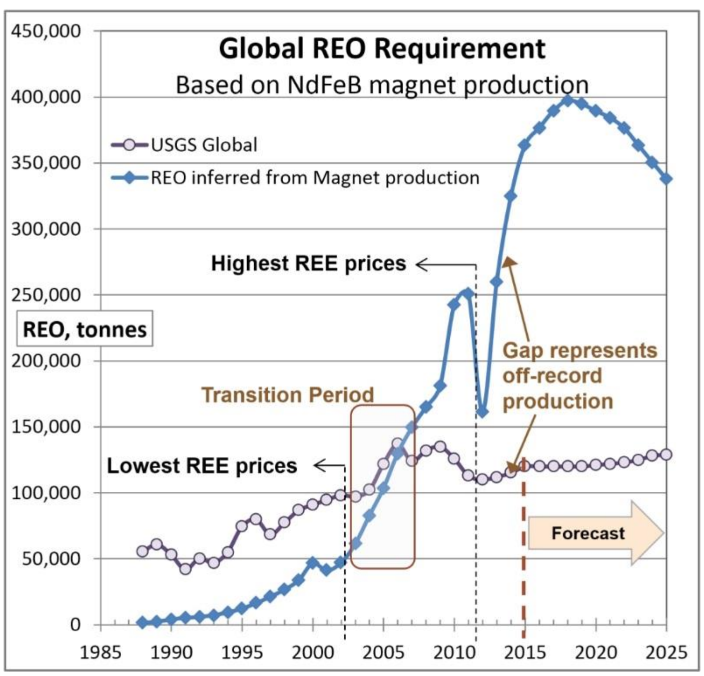


**Figure 3.** Global REO requirement based on actual and forecast magnet production

It is possible to estimate the quantity of magnets that can be produced based on the REO production, fraction of magnet REEs used to make magnets, and production yields converting to metals, alloys and magnets. Estimates shown in Figure 3 agree closely with magnet production estimates from within China from a bottoms-up approach.

At least three points can be made. First, there is a long period when REO output exceeded what was required to produce NdFeB magnets. This is a period when mining was driven to extract REOs for purposes other than for magnets.

The second point occurs in the early 2000s, what I call a transition period, when there was a closer match between REO output and magnet requirements. REO prices started a slow rise (2003 to 2007) due to the closer match between supply and demand.

The third point to make is the mismatch between published REO output from 2007 on and REO requirements to make the quantity of rare earth magnets reported by manufacturers. While most people might expect to see some black market activity, the apparent quantities are very large. For example, in 2015, the indicated size of the black market is roughly the same size as the published REO output.

A final note regarding the shape of the magnet production curve is that it peaks in 2018 due to the Weng model output. The peaking is, therefore, subject to the same caveats presented earlier, one of those being initiation of new sources of REO. The rapid rise to a requirement of over 350,000 tonnes of REO also indicates that the RE magnet market has the potential to grow above where it ended 2015 as long as the raw material supply is not curtailed.

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