Hindawi
Advances in Materials Science and Engineering
Volume 2018, Article ID 3149412, 9 pages
https://doi.org/10.1155/2018/3149412

Review Article

The Impact of Magnetic Materials in Renewable Energy-Related Technologies in the 21st Century Industrial Revolution: The Case of South Africa

Wallace Matizamhuka

Vaal University of Technology, Department of Metallurgical Engineering, Andries Potgieter Blvd, Vanderbijlpark, South Africa

Correspondence should be addressed to Wallace Matizamhuka; wallace@vut.ac.za

Received 1 September 2018; Accepted 8 October 2018; Published 1 November 2018

Academic Editor: Andres Sotelo

Magnetic materials specifically permanent magnets are critical for the efficient performance of many renewable energy technologies. The increased reliance on renewable energy sources has accelerated research in energy-related technologies the world over. The use of rare-earth (RE) metals in permanent magnets continues to be a source of greater concern owing to the limited RE supply coupled with dwindling reserves on the globe. This review focuses on how this has impacted on the state-of-the-art magnetic materials that continue to play a pivotal role in driving renewable energy technologies. Magnetic materials are perceived as key in driving the 21st century industrial revolution, and the participation of South Africa in this energy paradigm is critical in driving a new industrial revolution within the African continent. A number of opportunities are highlighted, and clarity is given on the several ubiquitous misconceptions and the risks on the heavy reliance on a single source for RE magnetic materials.

1. Introduction

In recent years, technology advancement focus has shifted towards renewables as the new energy source frontiers. Magnetic materials play a pivotal role in the efficient performance of devices in a wide range of applications such as electric power generation, transportation, air-conditioning, and telecommunications. The drive towards improving electricity transmission efficiency and the replacement of oil-based fuels by electric motors in transportation technologies has motivated researchers to focus on magnetic material technologies [1]. The increased demand for electricity in the past few decades will require a strong investment in energy-efficient power generation methods in some instances; lightweight and smaller sized devices are preferred such as in transportation and wind power [1]. The historical evolution of permanent magnetic materials spans over a 100-year period [1]. Manufacturing techniques of these magnets are well established, and the energy densities (a key figure of merit for permanent magnets) have been enhanced from ~1 MGOe for steels, increasing to ~3 MGOe for hexagonal ferrites, and peaking at ~56 MGOe for neodymium-iron-boron (Nd-Fe-B) magnets in the early 2000s [1]. The need for maximised energy densities at various operating temperatures has directed the research and development of rare-earth (RE) permanent magnets (RPMs) possessing improved temperature stability for electromotor applications [1]. However, due to the scarcity of RE magnetic metals such as Dy-dysprosium, Pr-praseodymium, and Sm-samarium, a more practical approach, which seems to be gaining more ground, is manipulation on the structure of grain boundary phases and internal interfaces, which enable better understanding of relevant coercivity mechanisms. Another approach is the development of textured nanocomposites, which may lead to the next generation of permanent magnets.

Although the relevance of this sector may be of little significance to the South African industry currently, it is indeed a reality that the world is moving towards cleaner and more efficient energy sources. As such, it is anticipated that a new industrial revolution will be ignited by such need, which will bring online specialised industries to meet the demand. In 2015, Stegan published a warning article on the concerns over the "rare-earth crisis" [2]. This was meant to serve as a wake-up call for decision-makers on the need to develop alternative supply chains for RE-based magnetic materials around the world. The present review, therefore, seeks to re-emphasise this need and make the South African policymakers, science and engineering community, and interested parties aware of the opportunities that lie ahead, which may require special funding, especially in research and development. The review provides a background on magnetic materials and further gives some highlights regarding the world market for magnetic materials. Special attention is given to RE-based permanent magnets as a key ingredient to the sustenance of the 21st century industrial revolution. The author also intends to clarify the several ubiquitous misconceptions and the risks of the heavy reliance on a single source for RE magnetic materials. The review concludes with an assessment of the available alternatives to address the shortages and the role South Africa can play in this rare-earth crisis.

2. Historical Background of Magnetic Materials

Over the years, society requirements have become more advanced and magnetic materials have become pivotal in the advancement of human civilisation. Magnetic product applications have evolved from the simple magnet distribution needs in the early 1930s to the more advanced high-performance motor applications in today's electric vehicles. A number of magnetic materials are available, ranging from the low-cost and low-energy ferrites to the more expensive and high-performance RE materials. Magnetic materials are generally classified in terms of their magnetic properties and uses. For instance, a material that is easily magnetised and demagnetised is referred to as a soft magnetic material, whereas a material that is difficult to demagnetise is referred to as a hard (permanent) magnetic material [3].

Since the 1930s, Alnico magnets have been widely used, initially in military electronic applications and later in civilian versions such as automotive and aircraft sensor applications. The development of Alnico magnets marked the beginning of a new way of thinking about magnetic materials where composite materials with multiple phases produced attribute superior to those of the individual components [4]. Alnico magnets are alloys mainly based on nickel, cobalt, and iron with smaller amounts of aluminium, copper, and titanium (typical composition in wt.%: Fe-35; Co-35; Ni-15; Al-7; Cu-4; Ti-4) [4]. They possess a fine microstructure consisting of micron- or submicron-scale ferromagnetic particles dispersed in a weak magnetic matrix [4]. They derive their magnetic strength by virtue of a phase separation in the alloy into ferromagnetic FeCo-rich and weakly magnetic NiAl-rich phases precipitated from the high-temperature homogenous composition [4]. To this date, the so-called "*supermagnets*" are based on this very principle [4].

In 1952, the Phillips Company (Eindhoven, Netherlands) announced the successful commercialisation of the first ceramic magnets [5]. These complex oxides are based on the prototypical composition $MO.6Fe_2O_3$ or equivalently $MFe_{12}O_{16}$ where M represents the divalent metals Ba, Sr, or Pb [4]. The most popular of these ceramic magnets is barium ferrite or barium hexaferrite ($BaFe_{12}O_{19}$) [4]. These magnets have commercial significance owing to their low cost and chemical inertness and because they are easy to process. They are classified as ferrimagnetics with both ferromagnetic (FM) and antiferromagnetic (AF) coupling between atomic moments, and the magnetic coupling depends on the specific crystallographic position of Fe ions [4]. However, the major drawback of these magnets is the decrease in magnetisation values with increasing temperatures, brittle behaviour, and low magnetisation values at room temperature [4]. This is offset by the high Curie temperature T_c~1223–1248°C (defined as the transition temperature from ferromagnetism to paramagnetism) making them suitable in areas of spintronic materials, battery cathodes, microwave communication, electric motors, and high-T_c superconductors [6–9].

In the mid-1960s, under the direction of Dr. Karl J. Strnat at the US Air Force Materials Laboratory later at the University of Dayton, Ohio, large magnetic products were reported in intermetallic compounds based on samarium-cobalt typically 5.1 MGOe (40.6 kJ/m^3) and later optimised to 18 MGOe (143.2 kJ/m^3 [10]. This family of compounds consisted of the general formula $RE(TM)_5$ containing RE metals Y-yttrium, Ce-cerium, Pr-praseodymium, Sm-samarium, and transition metal (TM) cobalt [4]. In 1972, further exploration resulted in the discovery of a new compound $RE_2(TM)_{17}$ the so-called "2–17" compounds [4]. $Sm_2(Co,Fe)_{17}$ was reported to possess a theoretical maximum energy product of up to 60 MGOe (477.5 kJ/m^3) [11]. The SmCo magnets were later commercialised with typical energy products in the range 22–32 GMOe (175–255 kJ/m^3) depending on the composition combined with an attractive Curie temperature (~750°C) making them suitable for high-temperature applications [12].

The drive towards neodymium-iron-boron ($Nd_2Fe_{14}B$) magnets was a result of the increased cost of Co in the late 1970s, a critical ingredient in the SmCo magnets [4]. Political instability in the DRC (former Zaire: source of 60 percent of Co world supply) in 1978 jeopardised the global supply of cobalt [4]. In 1982, the US Budget Office published a strategic policy option to minimise the US reliance on cobalt and to focus on cobalt substitutes for the manufacture of high-energy magnets [4]. In the mid-1980s, a new iron-based supermagnet $Nd_2Fe_{14}B$ (also known as *'Neo' or 2-14-1*) was produced simultaneously at General Motors US through a rapidly solidified synthesis method and at Sumitomo through a liquid phase sintering method [13–15]. Today the commercialised supermagnets based on RE intermetallic compounds $Nd_2Fe_{14}B$ have typical maximum energy products on the order of 56MGOe (~445.7 kJ/m^3) with remanence of B_r~14 kG (1.4 T) and intrinsic coercivity of H_{ci}~10 kOe (796 kA/m) [16]. To put this into perspective, most magnets used on souvenirs such as displays on refrigerators possess typical energy products of <1MGOe (8 kJ/m^3) [4]. Although these magnets achieved high-performance scores, they possess a marginal Curie temperature in the range of 300–400°C with an operating temperature restricted to ~150°C plagued by both brittleness and a large propensity to corrode [4]. Figure 1 shows the development cycle of magnetic materials as described above.

2.1. World Market for Permanent Magnets. In recent years, the choice of a permanent magnetic material for a given application is mainly based on a balanced consideration of price and performance [4]. The design goal for lightweight devices and smaller sizes has enabled NdFeB to be the magnet of choice for higher-end applications [4]. It is noteworthy to mention here that the fastest growing market for permanent magnetic materials is the energy-related applications [1]. The production of sintered NdFeB magnets has experienced a phenomenal growth from ~6000 t in 1996 to ~63,000 t in 2008 with the bulk of this (~80%) being produced in China [18]. The driving force behind the growth in demand for permanent magnets is the high-energy consumer electronic products such as DVDs, iPods, cameras, sensors, and cellphones [1]. The use of high-energy magnets enables the miniaturisation of these devices, which drastically reduces the electrical power requirements of such devices [1]. There are also other applications where NdFeB magnets have been used in large quantities such as in electric-assisted/electric vehicles (EAVs/EVs), speakers, magnetic separation units, windmill generators, magnetic resonance imaging (MRI), and electric bicycles [1].

Hexaferrite magnets have the largest global market share on a tonnage basis accounting to ~85 pct (by wt) of total sales by virtue of their much lower price [1, 4]. However, the NdFeB family of magnets remains the permanent magnet of choice for high-end applications and represents over 50 percent of magnet sales on a dollar basis (Figure 2) [19, 20]. A projection on the permanent magnet sales for the four major magnet types: Alnico, SmCo, ferrite, and NdFeB shows a quasiexponential growth from 1985 to 2020 with NdFeB magnet sales projected to be over \$17bn by 2020 (Figure 2) [19, 20].

The use of hard magnetic material NdFeB has offered quite significant performance benefits, which has enabled the development of highly efficient traction motors not possible with other technologies [21]. However, hard NdFeB magnets contain the RE Nd whose supply together with that of other RE metals (Sm-samarium, Dy-dysprosium, Gd-gadolinium, Pr-praseodymium, Pm-promethium, and Er-erbium) is environmentally unsustainable [21]. This has resulted in the prices of such RE metals soaring during the 2011–2012 period (Figure 3), raising a lot of concern over their continued use as ingredients for hard magnetic materials [21].

The discussion below provides insight on the current status and the efforts made so far in the search for alternative materials to replace the RE magnets.

2.2. Magnetic Materials in Renewable Energy Applications. Historically, the drive behind the development of permanent magnets emanates from the need to obtain high magnetic energy product over smaller volumes of magnets, which could be utilised in a number of technological applications such as clean energy technologies (wind turbine generators and hybrid regenerative motors), transportation components, and consumer products [4]. Magnetic materials play a pivotal role in modern society owing to their unique ability to perform a number of tasks as follows:

(i) Convert mechanical to electrical energy
(ii) Transmit and distribute electric power
(iii) Facilitate microwave communications
(iv) Provide basis for data storage systems

Theoretically, a strong permanent magnet is characterised by a large remnant magnetic flux (remnant or B_r), which must be maintained in the absence of a magnetic field coupled with a large resistance to demagnetisation (coercivity of H_c or intrinsic coercivity of ${}_iH_c$). Magnetic properties can be either intrinsic or extrinsic. Intrinsic magnetic properties are those determined by the crystal structure and composition of the material and are ideally insensitive to the material's microstructure. Such properties include saturation magnetisation, M_s, and magnetic ordering temperatures, i.e., ferromagnetic Curie temperature (T_c) and antiferromagnetic Neel temperature (T_N) [4]. T_c and T_N define the temperatures at which ambient thermal

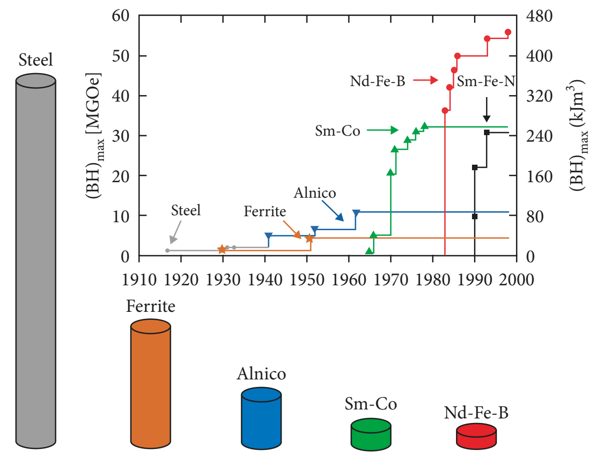

Figure 1: A schematic representation of the development cycle for permanent magnetic materials and a representation of different types of materials with comparable energy densities [17].

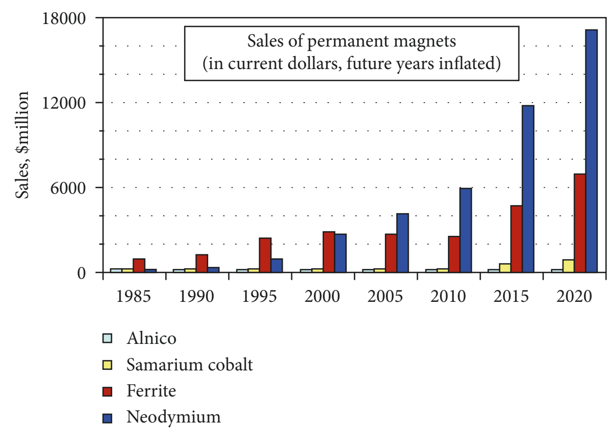

Figure 2: Projected growth in demand for permanent magnets from 1985 to 2020 [19].

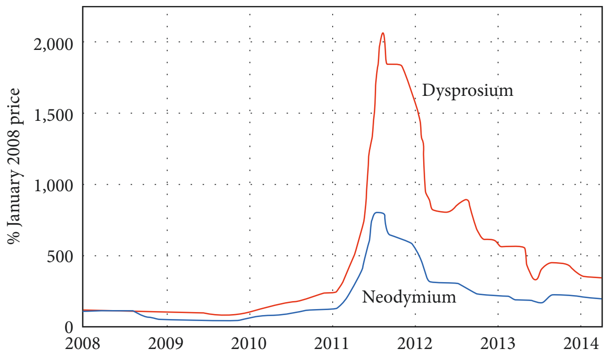

FIGURE 3: Price spike of RE metals experienced during the 2011–12 period as a result of controlled supplies [19].

energy becomes sufficiently large to destroy effective magnetic ordering. Key to the high performance of permanent magnets is that all the parameters mentioned above should be insensitive to temperature in order to maintain their integrity under elevated temperature operating environments [4]. A Curie temperature well above room temperature is more suitable, and the constituent materials should be preferably inexpensive, easy to process, lightweight, nontoxic, and corrosion resistant [22].

There is no doubt that policymakers, scientists, and other interested stakeholders around the globe are focused on reducing the reliance on hydrocarbon energy sources in favour of renewables [2]. A number of reasons have been cited, which include oil price volatility and economic vulnerability, concerns over global warming, and the general need for diversification in energy portfolios [2]. Permanent magnets find use in many renewable energy technologies and are key to the success of the renewable energy industry. An assessment by the US Department of Energy in 2011 on the criticality of REs to clean energy applications for both short-term (0–5 yrs) and medium-term (5–15 yrs) periods clearly indicates the importance of REs in the sustenance of renewable energy technologies [23]. A selected few REs relevant to the present review are summarised in the Table 1. Rare-earth elements (REEs) with the greatest severity of supply risk are considered critical, and those at medium or low risk are deemed near critical or not critical, respectively.

According to the World Wind Energy Association (WWEA) statistics, wind power is the fastest growing sector within the renewable energy sector [24]. Wind power capacity is expected to reach 1.9 mln MW in 2020. Permanent magnet is a key component in the construction of wind turbine generators used for transforming mechanical power into electrical power [1]. The design of wind turbine generator drive system (Figure 4) has evolved over the years to meet higher demands for greater energy yield, reliability, and lower maintenance requirements [25]. NdFeB permanent magnets enable the replacement of mechanical gearboxes in wind turbines with direct-drive (DD) permanent magnet generators thus reducing the overall turbine weight, cost of other components such as concrete and steel required to support heavy gearboxes, and a reduction in the number of moving parts which basically allows for greater reliabilities and efficiencies [2, 26].

The new design offers benefits such as lower volume and weight, higher operating efficiency, higher torque density, easiness to assemble and maintain, and 50% lower internal heat generation [27–29].

Since the invention of the "mixed drive autovehicle" by the German inventor Henri Pieper in 1905, there has been phenomenal progress made to the rudimentary design patented then [1]. Today, electric/hybrid electric vehicles (EVs/HEVs) have re-emerged as a realistic alternative to gasoline internal combustion vehicles [1]. The success of EVs is owed to the highly efficient permanent magnet motors used to run the power train of the EV. In 1997, HEV became mainstream with the launch of the Toyota Prius [21]. Today, other automobile manufacturers have launched their own EV/HEV brands such as BMW i3 and Nissan Leaf owing to improvements made in the technology over the years [21]. The use of hard magnetic material NdFeB offers quite significant benefits, which has enabled the development of highly efficient traction motors not possible with other technologies. Typical composition of NdFeB magnets used in traction motors is around $Nd_{22}Dy_{11}Fe_{6.5}B_1Cu_{0.1}$ by wt.% implying ~33wt.% comprises the precious RE elements [30].

The magnetocaloric effect (MCE) is an alternative refrigeration method, which makes use of adiabatic magnetisation [1]. The working principle of MCE is based on the concept that the temperature of a suitable material changes when magnetised or demagnetised [31]. Magnetisation of a magnetocaloric material is equivalent to the compression of gas (heating), while demagnetisation is equivalent to expansion of gas (cooling) [32]. The MCE is fast becoming the preferred refrigeration method of the future owing to a number of benefits in comparison with the compressor-based refrigeration method. The most prominent benefits of MCE refrigeration include absence of harmful gases, generation of much less noise, and that it can be built more compactly because the working material is solid (Figure 5) [1]. Moreover, it has been demonstrated that the cooling efficiency in magnetic refrigerators containing gadolinium (Gd) can reach 60 percent of the theoretical efficiency limit compared to only ~45 pct in the best gas-compression refrigerators [33].

Lastly, the use of soft magnetic materials in transformers for power generation and conversion for the electrical grid plays a pivotal role in electricity generation. The performance of soft magnets is material specific and is dominated by properties such as low coercivity and core losses, high saturation magnetisation, resistivity, and permeability, which makes these materials more attractive for the efficient transmission and distribution of electricity [1]. There are efforts to revolutionise the way power is delivered by designing advanced electric storage systems, smart controls, and power electronics for AC-DC conversion, referred to as "*smart grids,*" using a number of advanced materials and devices to provide greater efficiencies and more affordable and sustainable energy use for the long term [22, 34].

2.3. Sustainability of Permanent Magnets Supply in the 21st Century. The RE metals are pivotal in the production of RE supermagnets owing to their superior properties from the

Table 1: A summary of selected rare-earth elements, applications, and criticality to clean energy [2].

Atomic no.	Name	Type	Selected applications	Crustal abundance (ppm)	Criticality to clean energy: short/medium term
57	Lanthanum	Light	Battery alloys, lasers, phosphors	31	Near critical/not critical
58	Cerium	Light	Ni-metal hydride (NiMH) batteries for hybrid/electric vehicles, phosphor powders	63	Near critical/not critical
59	Praseodymium	Light	Permanent magnets, NiMH batteries, photographic filters	7.1	Not critical/not critical
60	Neodymium	Light	Permanent magnets, lasers, astronomical instruments	27	Critical/critical
62	Samarium	Light	Permanent magnets, reactor control rods	4.7	Not critical/not critical
65	Terbium	Heavy	Permanent magnets, lighting and display phosphors	0.7	Critical/critical
66	Dysprosium	Heavy	Permanent magnets, lasers, lighting	3.9	Critical/critical
67	Holmium	Heavy	Magnets	0.83	N/A/N/A
69	Thulium	Heavy	Magnets	0.3	N/A/N/A

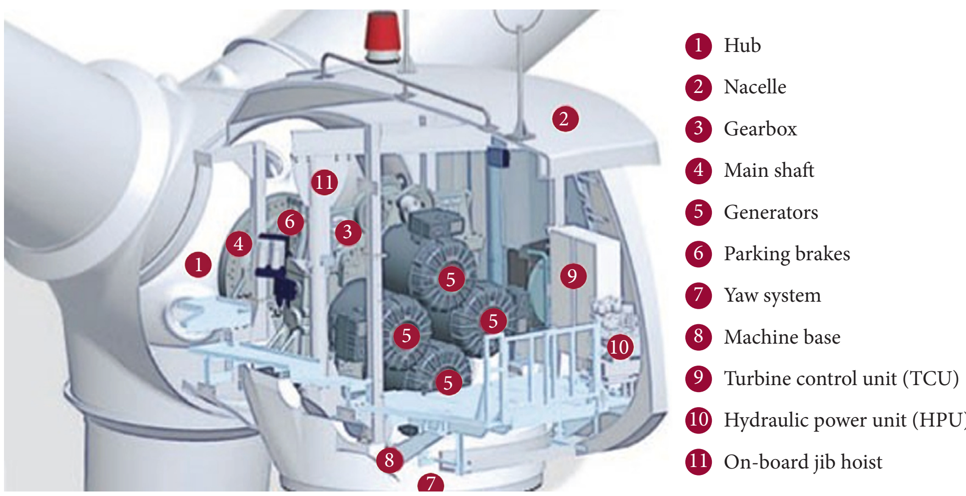

Figure 4: Exploded view of a typical 2.5 MW clipper wind turbine showing the position of four permanent magnet generators (5) [25].

high magnetisation provided by the 3d transition metal crystalline sublattice to the extremely strong magneto-crystalline anisotropy field provided by the 4f electrons [22]. RE elements consist of 17 chemical elements in the periodic table, namely, scandium (Sc), yttrium (Y), and 15 lanthanides. The lanthanides are categorised as light REs composed of elements with atomic numbers $Z = 57$ (lanthanum, La) to 61 (promethium, Pm), the medium RE elements ranging from $Z = 62$ (samarium, Sm) to $Z = 64$ (gadolinium, Gd), and lastly, the heavy RE elements include $Z = 65$ (terbium, Tb) through to $Z = 71$ (lutetium, Lu) [4]. The elements, which are key to the production of permanent magnets are Pr-praseodymium ($Z = 59$), Nd-neodymium ($Z = 60$), Sm-samarium ($Z = 62$), and Gd-gadolinium ($Z = 64$) for specialised applications and extremely important RE elements are Tb-terbium ($Z = 65$) and Dy-dysprosium ($Z = 66$) [4]. It is fascinating to note that the rarest elements in the earth's crust are not particularly the rare elements. For instance, cerium, which is part of the REs, is the 25th most abundant element of the 78 common elements in the earth's crust (~60 ppm) with the elements thulium and lutetium being the least abundant REs (~0.5 ppm) but are still more plentiful than the precious metals such as gold and platinum [1]. Of note is that a century ago, the RE elements were referred to as rare mainly because of their rarity, but nowadays, rare refers more to the difficulty in isolating single elements from their ores owing to their extremely similar physicochemical properties [2]. Moreover, the global distribution of REs is uneven with major world geologic supplies originating from a handful of sources (Table 2 and Figure 6) [4].

A recent analysis by the US Geological Survey indicates that China holds approximately 39 percent of the world's total reserves of REs accounting to 55,000,000 t with the rest distributed as follows: Brazil (22,000,000 t), the Commonwealth of Independent States (CIS) (19,000,000 t), the US (13,000,000 t), India (3,100,000 t), and Australia (2,100,000 t) with the remainder 25,800,000 t distributed among smaller reserves in Malaysia, Vietnam, and other countries [36, 37]. The RE global production stands at about 110,000 tpy of which China supplies 90 pct with the remaining 10 pct spread over smaller suppliers as follows: the US (~4000 tpy), India (~2900 tpy), Russia (~2400 tpy), and Australia (~2000 tpy) with smaller amounts from Brazil, Malaysia, and Vietnam [36, 37]. Currently, China is the only country in the world with the capacity to process heavy REs with its integrated supply chain developed over the past few decades [38].

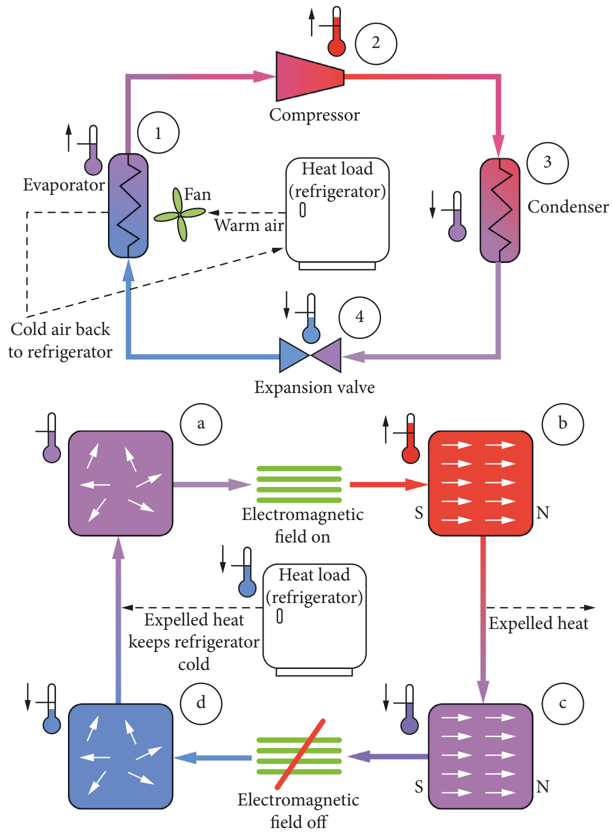

Figure 5: A comparison between the conventional vapour compression refrigeration (a) and magnetic refrigeration (b) [32].

Table 2: A summary of the world production and reserves of rare-earth elements in 2010 [4, 20].

Country	Mine production (metric tons)	Percent of total	Reserves (million metric tons)	Percent of total
China	130,000	97.3	55.0	50
United States	None	—	13.0	13
Russia	Not reported	Not reported	19.0	17
Australia	Not reported	Not reported	1.6	1.5
India	2700	2	3.1	2.8
Brazil	550	0.42	Small	—
Malaysia	250	0.27	Small	—
Others	N/A	22	—	20
Total	133,600	—	1100	

In 1995, a Chinese-based consortium acquired General Motors Magnequench-Delco Remy Division, created in 1986 to commercialise $Nd_2Fe_{14}B$ magnetic materials [39]. A mass exodus of RE magnet manufacturing capability from the US to China and subsequently an effective 'brain drain' of engineers and scientists [4] followed this.

It is estimated that the global RE industry was worth \$1,3 bn in 2010, whereas the end-user industries requiring REs are worth a lucrative ~\$4.8 trillion the same year [40]. This prompted the Chinese government to limit world exports of REs in a bid to attract more end use manufacturing industries to operate in China [40]. This spiralled the so-called rare-earth crisis in the late 2000s. In the year 2011, the US, EU, and Japan filed a WTO complaint against China of which China was found to have violated the international trade law by restricting overseas sales of REs [41].

Although the RE crisis is expected to subside over the years, the supply of REs for high-end applications will strategically remain important. Owing to the high demand for advanced permanent magnets to power high-end technologies, there is a clear shift in the future design paradigms towards low or zero RE content [4]. However, the complete substitution of REs in permanent magnets has proven problematic, and manufacturers and scientists are rather more focused on reducing RE content [2]. On the contrary, the complete elimination of REs in renewable technologies is a lengthy process, which can easily take a decade before complete replacement can be realised.

In recent years, the re-evaluation of mines outside China has taken the centre stage. With the currently prevailing attractive prices for REs, reopening mines has appeared attractive again [2]. One such mine is the Steenkampskraal mine in South Africa, which came online in the late 1950s, primarily producing thorium from an ore containing REs [2, 42]. The mine is currently being refurbished as an RE mine, and in 2014, it was reported that a pilot plant testing the extraction of REs has been preliminarily successful [42]. However, the US Department of Energy projected that the increase in demand for RE supplies in sufficient quantities will be required to offset the heavy reliance on Chinese mines [23]. In its 2013 survey, the US Geological Survey presented additional surveys for RE reserves within the African continent, which include Mozambique, Malawi, Madagascar, South Africa, and Tanzania [35].

2.4. Innovation of Alternative Permanent Magnetic Materials. It is no doubt that the use of RE metals Nd and Dy imparts high maximum energy product, resistance to demagnetisation, and high-temperature stability in $(Nd,Dy)_2(Fe,Co)_{14}B$ magnets in comparison with other magnetic materials [2, 21]. The maximum energy product is defined as a measure of the magnetic energy, which can be stored per unit volume by a magnetic material. Mathematically, it can be expressed as the product of the residual magnetic flux density (degree of magnetisation, M) and its coercivity (ability to resist demagnetisation once magnetised, H) [21]. It has been demonstrated that NdFeB magnets allow a very strong magnetic field to be generated in a very small volume. To put this into perspective, about five times less the cross-sectional area of NdFeB is required to produce the same magnetic field as an electromagnetic coil [21]. Moreover, an electromagnetic coil produces more losses in the winding arising due to electrical resistance of the conductor [21].

Although RE magnetic materials offer a number of benefits, it has been demonstrated that their replacement does offer some attraction in terms of cost, environmental footprint, and some aspects of performance [21]. There has been growing concern worldwide over the security of the

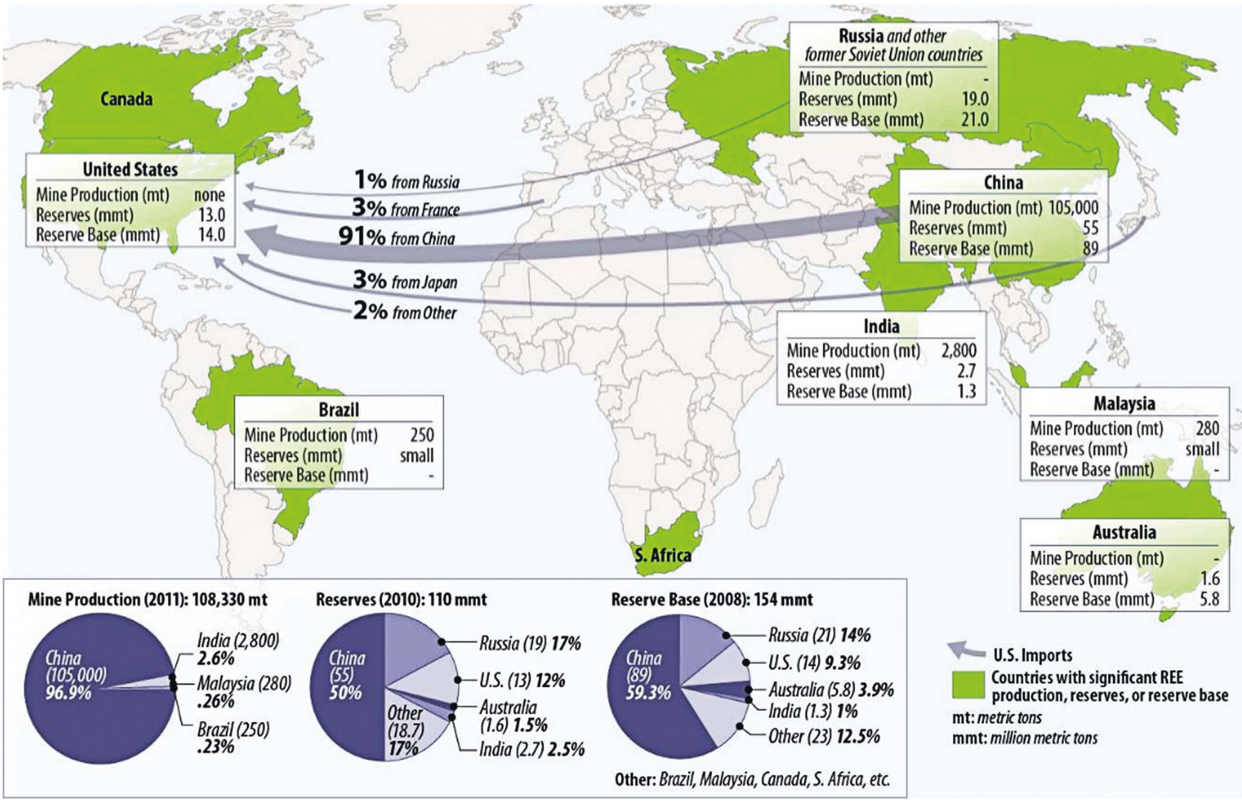

Figure 6: A representation of rare-earth world production, reserves, and US imports [35].

supply of REs critical to the manufacture of NdFeB magnets [43]. It must be noted, however, that a shift from REs may also trigger increased costs in the replacement metals, which could easily offset any benefits of eliminating REs [21]. A number of approaches are being examined to develop new RE-free magnet alloys and processing concepts to design structures that can match the magnetic properties of NdFeB permanent magnets.

Hitachi Metals developed a process, which involves the diffusion of dysprosium (Dy) into magnetic materials as opposed to direct alloying [44]. This effectively reduces the amount of Dy required in the magnetic products. There are reports on technologies based on size reduction into the nanorange to enhance the maximum energy product [45]. Design engineers have also used computer modelling to optimise electrical machine geometries, which in turn maximises power output whilst maintaining a low amount of REs required [44].

Lastly, it has been demonstrated that approximately 25 pct scrap is generated during machining of sintered magnets, and an enormous amount of this waste is discarded without attempting to recycle [46]. The current high prices of RE magnets have compelled producers to consider recycling, and a number of attempts are underway to develop technologies, which are efficient for the production of not only RE magnets from scrap but also disused magnets from old devices. There are two methods that have been developed to obtain powders from NdFeB waste-sintered magnets, namely, the hydrogen decrepitation (HD) process and the hydrogen decomposition desorption recombination (HDDR) process [18, 47, 48]. However, the major drawback is to develop high-coercivity anisotropic sintered magnets. Furthermore, the highly oxidised Nd-rich phases obtained during the recycling process are not well suited for the production of fully densified NdFeB magnets without some form of blending with purer phases [49]. In 2003, Kawasaki et al. reported that sintered magnets were successfully reproduced by blending jet-milled NdFeB with a $Nd_{80}Fe_{20}$ binary alloy [50]. Zakotnik et al. [51] added 1.0 wt.% Nd to recycled jet-milled NdFeB powders, which was sufficient to recover the magnetic properties through a hydrogen decrepitation (HD) method. Li et al. blended recycled milled NdFeB magnets with 24 wt.% $Nd_{22}PrFe_{14}B$ powder, which restored B_r to 99.2 pct, ${}_iH_c$ to 105.65 pct, and $(BH)_{max}$ to 98.65 pct [52, 53]. In two separate studies, the use of DyF_3 salt to produce $(Nd,Dy)_2Fe_{14}B$ shell on the surface of recycled powders was proposed [53, 54]. Recently, Sepehri-Amin et al. [49] reported a recycled magnet with a nominal composition $Nd_{21.63}Pr_{6.43}Dy_{3.42}Fe_{64.75}Ga_{0.1}Zr_{0.11}Al_{0.28}Co_{1.74}Cu_{0.32}B_{0.97}C_{0.12}O_{0.13}$ wt.% produced through a grain boundary modifier $Nd_2Fe_{14}B$ in powder form. The magnetic properties of the recycled magnet were reported to be superior to those of commercial NMX-43SH-grade sintered magnet. This was attributed to the formation of the distinct grain boundary phase and enrichment of ~0.8% at Dy in the shell of $Nd_2Fe_{14}B$ grains [49]. In all these studies, it is clear that the composition selection is quite critical to recover comparable hard magnetic properties.

3. Outlook

It is no doubt that the demand for RE permanent magnets is on the increase and there are a number of arguments that RE magnets may not offer the best long-term solution owing to the high cost and risk in the supply of critical rare-earth elements (REEs) used in permanent magnets. Moreover, some researchers have indicated that the influence of permanent magnets in motors may act as a source of inefficiency. However, in the author's opinion there exist opportunities in the supply chain development of RE magnets within South Africa in the short to medium term, provided the bigger players do not resort to predatory pricing behaviour to scare off emerging players as witnessed during the 2011-12 period. Furthermore, South African higher learning institutions need to step up their support by formulating specialised training for engineers and technologists in the area of magnetic materials including the research and development of such. There is indeed a critical skill shortage in this area world over. Research capability needs to be geared up towards finding alternative hard magnetic materials containing low or no REs, design of alternative technologies, and developing recycling technologies. Through such initiatives, some automotive manufacturers such as Renault and Tesla have successfully designed wound rotor and induction motor technologies, respectively, in their quest to finding alternatives to RE permanent magnets. In the long term, there is indeed potential of completely replacing RE magnets with low-cost ferrites with even higher traction. It is simply a matter of time and investing enough funding to achieve a level of design maturity commensurate with performance targets sought. In conclusion, South Africa can take advantage of this opportunity by collaborating with organisations in the know to enable the establishment of a niche-level 21st century industry within Africa.

Conflicts of Interest

The author declares that there are no conflicts of interest.

References

[1] O. Gutfleisch, M. A. Willard, E. Brück, C. H. Chen, S. G. Sankar, and J. P. Liu, "Magnetic materials and devices for the 21st century: stronger, lighter, and more energy efficient," *Advanced Materials*, vol. 23, no. 7, pp. 821–842, 2011.

[2] K. S. Stegen, "Heavy rare earths, permanent magnets, and renewable energies: an imminent crisis," *Energy Policy*, vol. 79, pp. 1–8, 2015.

[3] I. R. Harris and A. J. Williams, *Material Science and Engineering*, EOLSS, Vol. II, EOLSS, Oxford, UK, 2000.

[4] L. H. Lewis and F. Jimenez-Villacorta, "Perspectives on permanent magnetic materials for energy conversion and power generation," *Metallurgical and Materials Transactions A*, vol. 44A, no. S1, pp. S2–S20, 2013.

[5] J. Went, G. W. Rathenau, E. W. Gorter, and G. W. van Oosterhout, "Hexagonal iron-oxide compounds as permanent-magnet materials," *Physical Review*, vol. 86, no. 3, pp. 424-425, 1952.

[6] J. Goodenough, *Magnetism and the Chemical Bond, Interscience Monographs on Chemistry: Inorganic Chemistry Section*, Interscience, Geneva, Switzerland, 1963.

[7] A. Mann, "Still in suspense: a quarter of a century after the discovery of high-temperature superconductivity, there is still heated debate about how it works," *Nature*, vol. 475, no. 7356, pp. 280–282, 2011.

[8] J. Heber, "Materials science: enter the oxides," *Nature News*, vol. 459, no. 7243, pp. 28–30, 2009.

[9] S. A. Wolf, "Spintronics: a spin-based electronics vision for the future," *Science*, vol. 294, no. 5546, pp. 1488–1495, 2001.

[10] K. Strnat, G. Hoffer, J. Olson, W. Ostertag, and J. J. Becker, "A family of new cobalt-based permanent magnet materials," *Journal of Applied Physics*, vol. 38, no. 3, pp. 1001-1002, 1967.

[11] K. Strnat, "The hard-magnetic properties of rare earth-transition metal alloys," *IEEE Transactions on Magnetics*, vol. 8, no. 3, pp. 511–516, 1972.

[12] J. Zhou, R. Skomski, C. Chen, G. C. Hadjipanayis, and D. J. Sellmyer, "Sm–Co–Cu–Ti high-temperature permanent magnets," *Applied Physics Letters*, vol. 77, no. 10, pp. 1514–1516, 2000.

[13] J. Croat, "Bonded rare earth-iron magnets," US Patent 4902361 A, 1986.

[14] Y. Matsuura, "Process for producing permanent magnet materials," US Patent 4597938, 1986.

[15] N. C. Koon, "Hard magnetic alloys of a transition metal and lanthanide," US Patent 4402770, 1983.

[16] J. M. D. Coey, *Magnetism and Magnetic Materials: Principles and Applications*, Cambridge University Press, New York, NY, USA, 2010, ISBN-13: 978-0521816144.

[17] O. Gutfleisch, "Controlling the properties of high energy density permanent magnetic materials by different processing routes," *Journal of Physics D: Applied Physics*, vol. 33, no. 17, pp. R157–R172, 2000.

[18] O. Gutfleisch, K. Güth, T. G. Woodcock, and L. Schultz, "Recycling used Nd-Fe-B sintered magnets via a hydrogen-based route to produce anisotropic resin bonded magnet," *Advanced Energy Materials*, vol. 3, pp. 151–155, 2013.

[19] Arnold Magnetic Technologies, http://www.arnoldmagnetics.com/.

[20] M. Humphries, *Rare Earth Elements: The Global Supply Chain Congressional Research Service Report 7-5700*, 2013, http://www.crs.gov.pp.R41347.

[21] J. D. Widmer, R. Martin, and M. Kimiabeigi, "Electric vehicle traction motors without rare earth magnets," *Sustainable Materials and Technologies*, vol. 3, pp. 7–13, 2015.

[22] Litos Strategic Communication under DOE contract DE-AC26-04NT41817. The Smart Grid: An Introduction, http://www.oe.energy.gov/DocumentsandMedia/DOE_SG_Book_Single_Pages(1).pdf.

[23] US DOE (US Department of Energy), *Critical Materials Strategy*, US Department of Energy, Washington DC, USA, 2011, http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf.

[24] World Wind Energy Association, http://www.windea.rg, report from March 2010.

[25] Clipper Windpower, http://www.clipperwind.com/pdf/liberty_brochure.pdf.

[26] R. Kleijn, "Materials and energy: a story of linkages. Materials requirement of new energy technologies, resource capacity, and interconnected materials flow," PhD Thesis, Leiden University, Netherlands, 2012, https://openaccess.leidenuniv.nl/handle/1887/19740.

[27] S. Makaremi, *Clipper's Design Approach to Improving Reliability*, Clipper Windpower, Inc, Cedar Rapids, IA, USA, 2007.

[28] G. Bywaters, V. John, J. Lynch, P. Mattila, G. Norton, and J. Stowell, *Northern Power Systems Wind PACT Drive Train Alternative Design Study Report (2005)*, National Renewable Energy Laboratory, Golden, CO, USA, 2005, http://www.nrel.gov/docs/fy05osti/35524.pdf.

[29] E. De Vries, *Danes Hail Lidar Breakthrough in Wind*, Renewable Energy World Int. Magazine, 2010, https://www.renewableenergyworld.com/articles/2010/03/danes-hail-lidar-breakthrough-in-wind.html.

[30] K. Hono and H. Sepehri-Amin, "Strategy for high-coercivity Nd-Fe-B magnets," *Scripta Materialia*, vol. 67, pp. 530–536, 2012.

[31] Toyota Motor Corporation, *Public Affairs Division, "Toyota Hybrid System"*, Toyota Motor Corporation, Japan, 2003.

[32] H. C. Singal, A. Mahajan, and R. Singh, "Magnetic refrigeration-a review-a boon for the coming generations," *International Journal of Mechanical Engineering*, vol. 3, no. 5, pp. 46–52, 2016.

[33] C. Zimm, A. Jastrab, A. Sternberg et al., "Description and performance of a near-room temperature magnetic refrigerator," *Advances in Cryogenic Engineering*, vol. 43, pp. 1759–1766, 1998.

[34] US Department of Energy, *Grid 2030-A National Vision for Electricity's Second 100 Years*, Office of Electric Transmission and Distribution, US Department of Energy, USA, 2003.

[35] USGS (US Geological Survey), *2011 Minerals Yearbook: rare earths*, US Department of Interior, Reston, Virginia, USA, 2013, http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/.

[36] USGS (US Geological Survey), *The Rare Earth Elements-Vital to Morden Technologies and Lifestyles. Fact Sheet 2014-3078*, US Department of Interior, Reston, Virginia, USA, 2014, http://pubs.usgs.gov/fs/2014/3078/.

[37] USGS (US Geological Survey), *Mineral Commodity Summaries 2014*, US Department of the Interior, Reston, Virginia, USA, 2014, http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2014-raree.pdf.

[38] J. Lifton, "Where are the non-Chinese heavy rare earths going to come from and who's going to buy them?," *News Analysis, Rare Earths*, 2012.

[39] Neo Materials Technologies, http://www.magnequench.com.

[40] J. Seaman, *Rare Earth and Clean Energy: Analysing China's Upper Hand. IFRI Working Paper*, L'Institut Français des Relations Internationals, Paris, France, 2010, http://www.ifri.org/downloads/noteenergieseaman.pdf.

[41] D. Jolly, *China Export Restrictions on Metals Violate Global Trade Law, Panel Finds*, The New York Times, New York, NY, USA, http://nytimes.com/2014/03/27/business/international.

[42] GWMG (Great Western Minerals Group), *Great Western Minerals Successfully Produces Rare Earth Carbonate from Mini Pilot Plant Testing*, GWMG (Great Western Minerals Group), Saskatoon, Canada, 2014, http://www.gwmg.ca/investors/news.

[43] K. Bourzac, *The Rare-earth Crisis. MIT Technology Review*, vol. 114, no. 3, pp. 58–63, 2011, http://www.technologyreview.com/featuredstory/423730/the-rare-earth-crisis/.

[44] R. Gehm, *Hitachi Metals Reduces Rare-earth Dysprosium in Electric-Motors Magnets*, SAE International, Pittsburgh, PA, United States, 2013, http://articles.sae.org/11988.

[45] S. Kozawa, *Trends and Problems in Research of Permanent Magnets for Motors-Addressing Scarcity Problem of Rare Earth Elements*, 2010, NISTEP Science & Technology Foresight Center, http://data.nistep.go.jp/dspace/bitstream/11035/2854/1/NISTEP-STT038-40.pdf.

[46] K. Miura, M. Itoh, and K. I. Machida, "Extraction and recovery characteristics of Fe element from Nd–Fe–B sintered magnet powder scrap by carbonylation," *Journal of Alloys and Compounds*, vol. 466, no. 1-2, pp. 228–232, 2008.

[47] E. A. Perigo, S. C. da Silva, R. V. Martin, H. Takiishi, and F. J. G. Landgraf, "Properties of hydrogenation-disproportionation-desorption-recombination NdFeB powders prepared from recycled sintered magnets," *Journal of Applied Physics*, vol. 111, no. 7, article 07A725, 2012.

[48] R. S. Sheridan, R. Sillitoe, M. Zakotnik, I. R. Harris, and A. J. Williams, "Anisotropic powder from sintered NdFeB magnets by HDDR processing route," *Journal of Magnetism and Magnetic Materials*, vol. 324, pp. 63–67, 2012.

[49] H. Sepehri-Amin, T. Ohkubo, M. Zakotnik et al., "Microstructure and magnetic properties of grain boundary modified recycled Nd-Fe-B sintered magnets," *Journal of Alloys and Compounds*, vol. 694, pp. 175–184, 2017.

[50] T. Kawasaki, M. Itoh, and K. Machida, "Reproduction of Nd-Fe-B sintered magnet scraps using a binary alloy blending technique," *Materials Transactions*, vol. 44, no. 9, pp. 1682–1685, 2003.

[51] M. Zakotnik, I. R. Harris, and A. J. Williams, "Multiple recycling of NdFeB-type sintered magnets," *Journal of Alloys and Compounds*, vol. 469, no. 1-2, pp. 314–321, 2009.

[52] X. T. Li, M. Yue, W. Q. Liu et al., "Large batch recycling of waste Nd–Fe–B magnets to manufacture sintered magnets with improved magnetic properties," *Journal of Alloys and Compounds*, vol. 649, pp. 656–660, 2015.

[53] T. S. Jang, D. H. Lee, A. S. Kim, S. Namgung, H. W. Kwon, and D. H. Hwang, "Recovery of high coercivity of the powders obtained by crushing Nd–Fe–B sintered magnet scraps," *Physica Status Solidi (A)*, vol. 201, no. 8, pp. 1794–1797, 2004.

[54] H. W. Kwon, I. C. Jeong, A. S. Kim et al., "Restoration of coercivity in crushed Nd-Fe-B magnetic powder," *Journal of Magnetism and Magnetic Materials*, vol. 304, no. 1, pp. e219–e221, 2006.