Sustainability of Permanent Rare Earth Magnet Motors in (H)EV Industry

1 Gwendolyn Bailey Department of Materials Engineering , KU Leuven, Leuven. Belgium
2 Nabeel Mancheri Institute of Environmental Sciences Leiden University, The Netherlands
3 Karel Van Acker Department of Materials Engineering, KU Leuven, Leuven, Belgium

Abstract

It is clear that hybrid/electric vehicles [(H)EVs] are only as green as the materials and energy that they use. According to MIT, the production and processing of rare earth elements (REEs) found in (H)EVs come with their own hefty environmental price tag (K. Bourzac, "The Rare-Earth Crisis," MIT Technol. Rev., 114(3):58–63, 2011). These damages include radioactive wastewater leaks and 'slash-and-burn processes' required to manufacture and separate REEs. Some life cycle assessment (LCA) studies found that the carbon advantage of an electric vehicle over an internal combustion engine vehicle is small considering the production/manufacturing and end-of-life stages (C.-W. Yap, "China Ends Rare-Earth Minerals Export Quotas," Wall Street Journal, updated 5 Jan. 2015; D.S. Abraham, "The War Over the Periodic Table," Bloomberg View, 23 Oct. 2015). However, sustainability is not only about environmental impacts, but also concerns other sustainable development principles such as economic viability and social well-being. Permanent magnet (PM) rare earth motors are most widely used in the (H)EV industry, but the price volatility of REEs does not make them an economically sustainable option. The research involving the potential social impacts of the extraction and use of rare earths for the automobile industry is examined. This review addresses the technical aspects of PM motors and how it contributes to or withdraws from the sustainability of (H)EVs. This paper undertakes a review of the literature and the present situation of sustainability of REEs in the electric vehicle industry. Furthermore, this paper highlights the areas of sustainability research considered by academic and industrial representatives to be essential for cleaning up the clean technology. The intention is not to declare rare earth PM motors sustainable, but to analyze their contribution to sustainability in terms of technical, social, environmental, and economic aspects. Ultimately, the potential opportunities toward a more sustainable rare earth PM motor are revealed.

Keywords

Rare Earth ; Life Cycle Assessment; Induction Motor; Life Cycle Assessment Study; Sustainability Assessment

Introduction

Rare earths have been used in the car industry for over 20 years, but they have not been of considerable interest until recently. In 2010, the world woke up to discover that China, the largest producer and holder of REE reserves, had slashed the REE export quota by 40%, tightening the belt another notch on their already heady monopoly [2, 3, 4]. During this time of panic, and amid the headlines such as the 'War Over the Periodic Table' and 'EU stockpiles rare earths,' the focus was given to the criticality of REE supply [5, 6]. Automobile industries reacted by scrambling for different solutions to avoid relying on rare earth exports by China. For example, Honda started extracting rare earth metals from used nickel metal hydride batteries [7]. Some electric vehicle applications have chosen to forgo magnets in their design by using an induction motor (IM), which will be discussed in the technical section. While there are many magnets throughout the hybrid and electric vehicle [(H)EV], the NdFeB permanent magnets (PMs) found inside the motor/generator, specifically those inside the rotor, are the focus for this paper.

It has been suggested that the shift toward electric and hybrid vehicles could make EV traction motors the main application for REE by 2050. Hybrid cars are currently dominating the automotive hybrid and electric market [8]. Permanent rare earth magnets are critical to many sustainable technologies; however, motors for use in small automotive and industrial applications remain the most important group in terms of absolute neodymium–iron–boron, or NdFeB, volumes [8]. Among different types of PMs, NdFeB has the highest energy density available and presently dominates the market in terms of value.

Figure 1 shows that the largest applications of PMs are in motors and generators such as engine components, battery components, moving car parts, and other integral systems [10]. There are around 40 magnets in motors and actuators, and 20 sensors in a typical car. REE magnets provide the best solution for many automotive applications and considered to be the top technology choice for the electric vehicle industry.

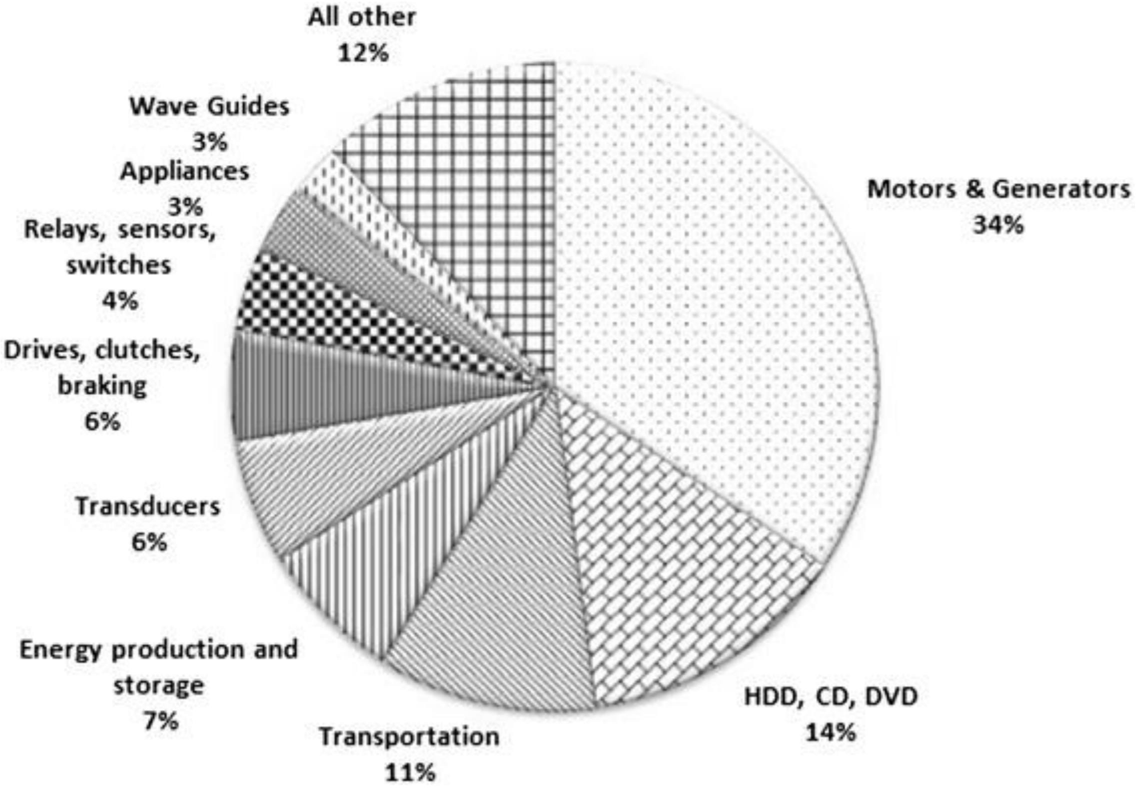


Fig. 1

Rare earth magnets by application.

Reproduce this figure obtained by Constantinides [9]

The global automotive industry is on a gradual transformative path as most of the original equipment manufacturers, or OEMs, are introducing new models of (H)EVs in the market. Thus far, the most successful (H)EVs have REE motors, including a majority of newly introduced models like Nissan Leaf, except Tesla, which does not use any REEs in its motor. Other companies are choosing to recycle REEs from end-of-life vehicles. Several years ago, Toyota, Honda, and Mitsubishi announced their campaign to start recycling rare earths; however, the status of their recycling activities is not advertised [7, 11].

Global trend on vehicle sales shows that smaller, highly fuel-efficient vehicles' sales are on the rise. Consumers who are more environmentally conscious than before no longer demand conventional large vehicles, and all major car manufacturers are adapting to this trend by introducing new (H)EVs to the existing brands [12]. For example, in the case of Toyota, more than one-fifth of all new vehicles sold by the manufacturer in the EU were hybrid electric in 2013 [13]. A report by the International Council on Clean Transportation Europe calculates that in Japan about 20% of all new car sales in 2013 were hybrids, and in the US the share of hybrid electric passenger cars was around 6% [13]. If the trend continues, then (H)EVs with dual-functionality engines will become dominant, replacing conventional internal combustion engines, which would possibly increase the demand for certain REEs [14]. Not only businesses but also governments have recognized the increasingly important role that (H)EVs are playing in modern society. Recently, the Netherlands have set a legislation in place with the goal of increasing electric vehicle sales, ultimately pushing for all vehicles on roads to be electric by 2030 [13].

Introducing new models of HEV and EVs is part of the global automotive industry's efforts to reduce CO_2 emissions along with other measures such as thermal efficiency improvement in internal combustion, transmission, and weight reduction. Figure 2 demonstrates that there will be a 35% improvement in CO_2 reduction from the sales of (H)EVs by 2025 and this would certainly increase the demand for certain REEs. Last year at the United Nations COP21 Climate Change conference, the European Automotive Manufacturers Association (ACEA) explained in their position paper that "a more 'comprehensive' approach is necessary to address all the aspects of use phase of a vehicle" [16]. However, the use phase is not the only aspect of electric vehicles which need attention, and focusing exclusively on utilization is no longer sufficient.

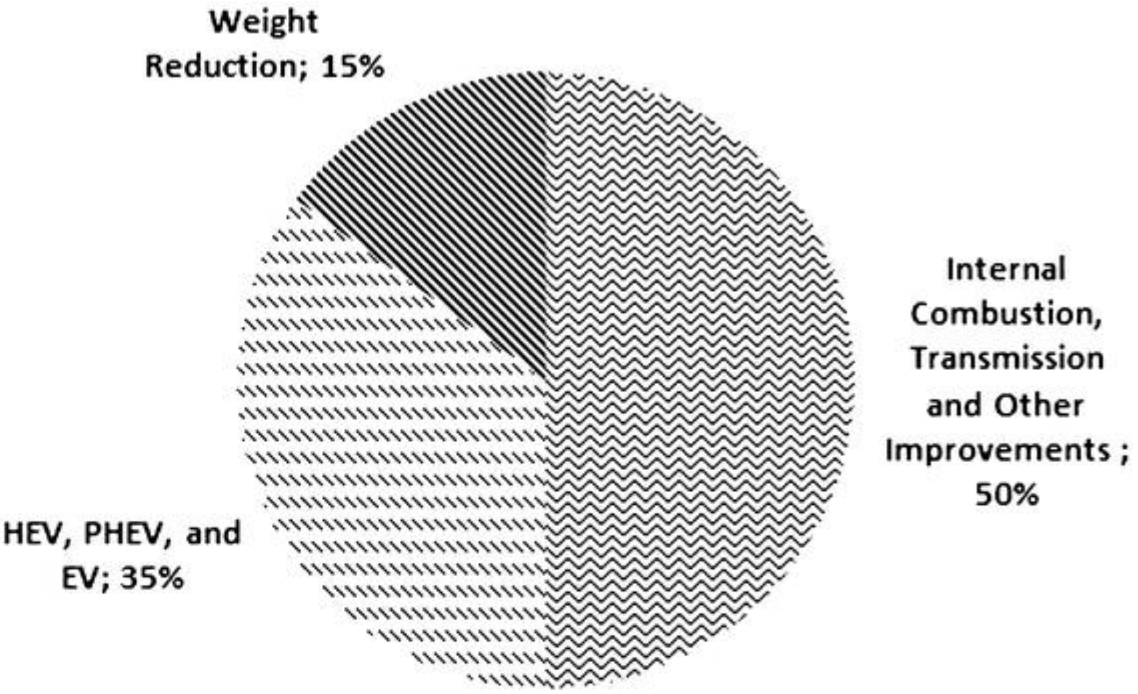


Fig. 2

2025 Sources of improvement in CO_2 reduction and real fuel economy.

Source: [15]

The book-ends of the rare earth PM motor process—manufacturing and end-of-life phases—must also be counted. The sociopolitical–economic and environmental aspects of the manufacturing of EVs and especially their PM motors need decoding. This can be done by performing an analysis on the sustainability of PM motors. To our knowledge, no sustainability assessment has been proposed for PM motors. Sustainability assessment can be defined as the process of identifying, predicting, and evaluating the potential impacts of initiatives and alternatives [17]. The possibility to assess products and processes is particularly important for a sector as inertial as that of the automobile industry. Since the "greenness" of the (H)EV has been called into question [18], we researched whether the use of the PM motor could contribute to tarnishing of the (H)EV image, or polish it. Thus, in order to discern whether the (H)EV industry is making its proper contribution to sustainability, we have presented a review of the literature and analysis of the state of play of sustainability of permanent rare earth magnet motors in the (H)EV industry.

Technical Background

Sources vary on the share of REEs used to make PM motors, but a combination of extensive literature research and modeling indicates that 21–36% of the world's REE production is used to make PM motors [10, 19]. The weight of a NdFeB magnet in a single EV motor is around 1 kg [20]. Neodymium, a light rare earth (LREE), is the leading element in the NdFeB magnets with iron used as a transition metal. REEs are the 15 elements which are found at the bottom of the periodic table and sometimes includes yttrium and scandium. The term rare is a misnomer and they are only rare in their chemical composition [8]. Since REEs all occur together, they are difficult to separate [21]. The weight percentage of total rare earths in NdFeB magnets is approximately 31%, which includes a certain amount of dysprosium depending on the application [21]. For higher temperature applications, and particularly in the direct drive wind turbines, neodymium is partially substituted with dysprosium, a heavy rare earth (HREE), well beyond 5% by weight. NdFeB magnets with a higher ratio of dysprosium are widely used in the motors and generators of (H)EVs for their combustion engine-electric motor dual functionality. (H)EVs benefit from greater amounts of dysprosium to reduce the size of their large motor assembly. Dysprosium is used in order to increase the intrinsic coercive force of the material (Hci) or to increase the resistance to demagnetization as the engine environment requires NdFeB with higher temperature grades [10].

Methodology

The literature relating to permanent rare earth magnet motors was extensively reviewed from both academic and industry standpoints. Due to the lack of literature on the sustainability of REEs in the EV industry, we concentrated on examining the literature covering four associated categories: environmental, social, economic, and technical aspects of REE PM motors in the (H)EV supply chain. This methodology was appropriated for the author's use from the framework put forth in a conference paper by B.C. McLellan [22]. The first three of these categories, the three Ps—people, profit, and planet—follow the widely acknowledged triple bottom line approach. However, one element not included in a typical sustainability report is the technical aspect. We argue that this should be included because if a product or system presents challenges because of its state of technology, then it is less durable, ergo less sustainable. It is known that the main issue preventing (H)EVs from making a proper contribution to sustainability is associated with technical feasibility in the field of recycling. It is less known how the technology of the motor itself contributes to sustainability. Thus, we acknowledge the literature focusing on the technical aspects of permanent rare earth magnet in (H)EV motors versus other types of motors used in EVs as well as the recycling methods.

Results: Environmental, Social, Economic, and Technical

The results of the review are organized below under their respective thematic heading.

Environmental

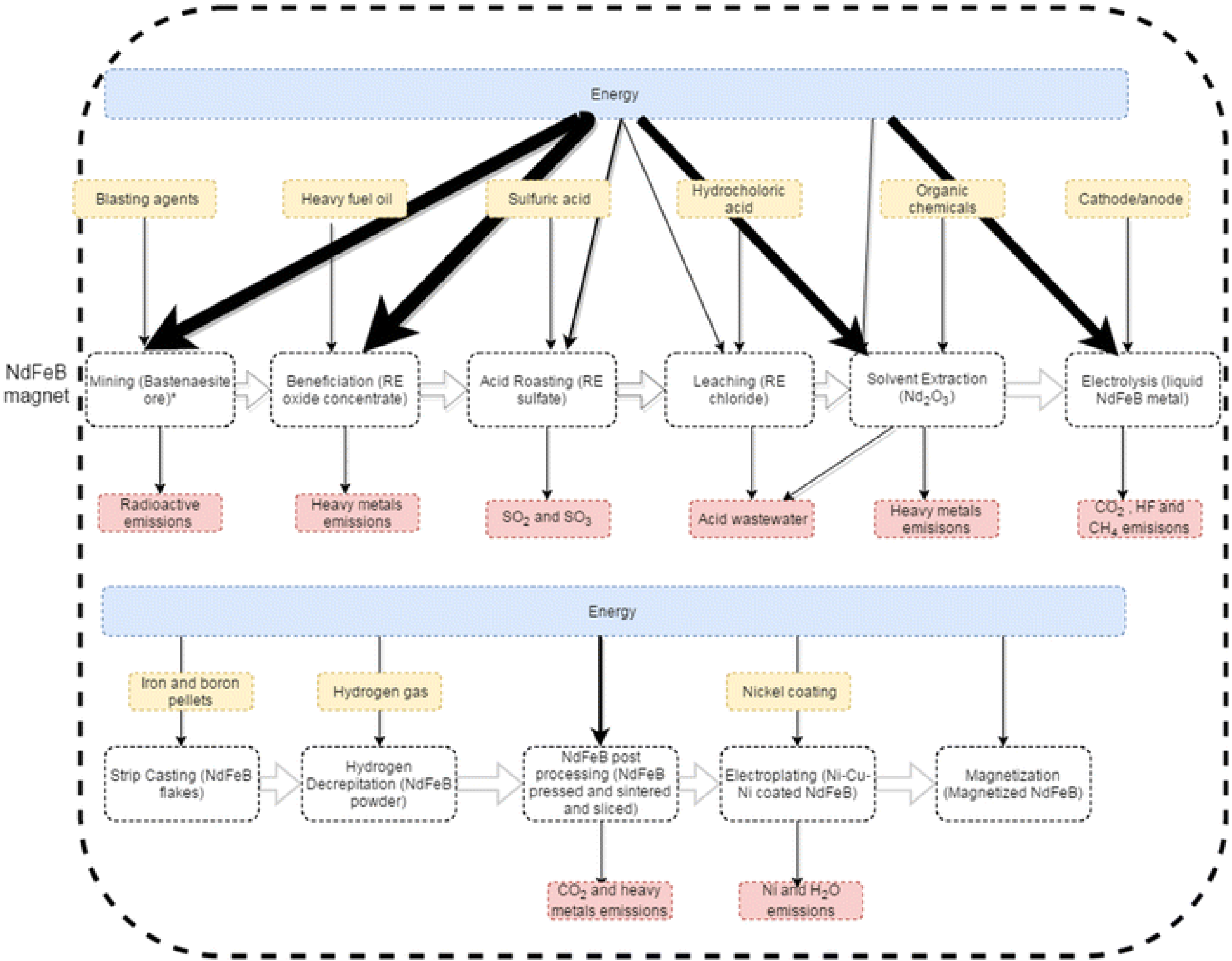
The following discussion explores the aspects of environmental sustainability within the value chain—from production, use, end-of-life of the rare earth PM motors. The source of materials and energy matter in the environmental footprint of EVs. With regard to materials in the EV motor production phase, there are no published data on exact locations of resources and their compositions due to company's change to confidentiality. But what we do know is that 75% of the materials are still largely coming from primary, virgin sources [23]. The bill of materials for the PM motor consists mostly of stainless steel, but the magnet embedded within the rotor is made up of rare earths which usually are co-mined with iron ores. The RE industry as a whole is highly reliant on finite stocks of bastnasite ores (a rare earth fluorocarbonate (Ce, La)(CO_3)F) and monazite ores (a rare earth phosphate (Ce, La, Y Th) PO_4), which is made up of a majority of Chinese feedstock [24, 25]. These geological reserves exist around the world, that is, not solely in China. The LREEs are more abundant and concentrated than HREEs [24]. Lee and Wen [26] suggest that more energy goes into extracting and Weng [27] processing the HREEs than the LREEs.

Mining

For the production stage, a Chinese article explains that there are indeed heavy metals which are emitted into groundwater during the mining process (namely cadmium and lead), and this increased heavy metal concentration can have effects on aquatic eco-toxicity levels [28]. There can be large amounts of toxic waste [29] and radioactive waste associated with the production of REEs [30]. This is a potential environmental health and safety concern. In fact, many assume that a major reason why REE production has been monopolized by China is because of the lackadaisical or worse, unenforced environmental regulation [31, 32]. The costs for scrubbers and other depolluting infrastructures, which are mandated in many Western countries, drive up the price of the product, which makes it difficult for the Western RE market to compete.

The HREEs, in particular, are extracted in an environmentally troubling way. They are extracted by a leaching process, which is sometimes referred to as 'slash and burn' [33]. The details of this process are not published, but a simple explanation of a general REE extraction process is as follows: Chinese mining companies flood the ground with toxic chemicals and then drain it [33]. The REEs get collected in the drained liquid and then the Chinese add other organic chemicals into these ponds to precipitate out the REEs [26]. Once the REEs are precipitated, the mining company leaves behind the ruined earth and tailings ponds. However, the Chinese are now cracking down on this [34, 35].

The processes associated with the extraction stage of REEs are mining, mineral beneficiation, roasting, and leaching which are represented in Fig. 3. These processes involve significant environmental costs for energy and solvents and effluent, radioactive material and hazardous waste handling. A simplified flowsheet of the NdFeB magnet production route from mining and extraction to processing is shown in the figure. The energy intensity is marked by the corresponding thickness of the arrows. From the flowsheet, it is easy to conclude that the making of PM magnet is energy and material intensive.



*Other ore types exist for REE extraction, this only shows the non ion-adsorption case

Fig. 3

Diagram of a simplified material flow analysis of NdFeB magnets.

Data from [36]

Use Phase

The following discussion focuses on the sustainability of (H)EV motors in the use phase. While (H)EVs tend to have the image of a very low environmental footprint for their use phase, they are, in fact, only as green as the energy used to power them [37, 38]. A Union of Concerned Scientist report, which takes into account the full life cycle assessment (LCA) of a Nissan Leaf EV, demonstrates that in areas where the electric utility relies on natural gas, nuclear, hydropower, or renewable sources to power its generators, the potential for electric cars and plug-in hybrids to reduce carbon dioxide emissions is great [38]. However, where (H)EVs are plugged into generators powered by burning a high percentage of coal, electric cars may not be even as good as the latest gasoline models, or even hybrids. LCA, which is a methodology used to measure environmental impacts throughout each stage of a product or systems life cycle, sometimes makes conclusions which may not be so evident, such as EVs may not be more environmentally friendly than their competing fuel-efficient internal combustion engine vehicles. Of course, one of the downfalls of LCA studies is that they do not give regionalized results, and they rarely address the impact of regional energy grid mixes. While many parts of Western civilization are still powered by coal-burning plants, electricity technology is moving toward employing cleaner energies such as natural gas, nuclear, hydroelectric, wind, or solar facilities. “To prevent the worst consequences of global warming,” the report concludes, “the automotive industry must deliver viable alternatives to the oil-fueled internal-combustion engine” [38].

We have examined the use phase of the typical PM motor, but as one may know one must evaluate all phases of a product and compare it with similar products before determining its contribution to sustainability. There are different types of these EV motors and we will briefly review which type presents the more sustainable option. Considering the negative environmental impact of PM making, there are some who wonder whether an electric motor can be constructed without the environmental drawbacks of the REE-based PMs [20]. IM contain no permanent magnetic materials, instead they operate by inducing electric currents in conductors in the motor’s rotor, and these currents in turn give rise to a magnetic field in the rotor, producing torque. However, IM take all their energy from the supply since they have no magnets producing energy.

IM incur losses in their rotor conductors, which can result in total rotor losses two to three times higher than that in a PM-based motor. This implies that IM efficiency is lower than PM motor. For instance, at 6000 rotations per minute, in [39] the IM motor has been shown to have an efficiency of 83% and the PM to have an efficiency of 91%. More examples of alternative motors for (H)EVs include wound rotor motors, switched, and synchronous reluctance motors. However, these are not often favored because these motors have variation in reluctance and can have unwanted vibration and noise. Moreover, the efficiencies of these motors are somewhere between IM and PM motor [40]. It is important to note for the PM-assisted synchronous reluctance motor, the power factor is greater than IM. In fact, one can employ ferrite magnets instead of rare earth PMs in this motor and still have an improved efficiency over IM. This proves that the presence of magnet improves power factor as well as efficiency. Despite this clear advantage, rare earth PM motors and IM are still the two most common commercially available (H)EV motors.

End-of-Life

Recycling technologies for PMs simply are not advanced enough to be considered economically viable or even sustainable. Current recycling of the PMs is very minimal and practices exist only with return of minor amounts of scrap material to the alloy manufacturing plant [41]. Effort to recycle the end-of-life products containing NdFeB yields a small return, and their physical extraction is difficult as these magnets are brittle intermetallics, which are deeply embedded and sometimes glued onto other products. Despite these challenges, development of new magnet technologies and new cost effective and innovative recycling technologies are being pursued [42, 43, 44]. But most of the time, recycling efforts for these PM motors are not viewed as worth the cost. And even liberating and recycling some of these PMs via pyrometallurgical or hydrometallurgical techniques could emit harmful gases or sludge. Contrary to a popular belief, recycling could even be seen as harmful to the environment in this case.

The potential environmental impact of recycling NdFeB magnets has been reviewed in several recent studies [21, 45, 46]. Benjamin Sprecher’s life cycle study looks at the complete energy and environmental impacts of producing a kilogram of the rare earth metal neodymium for magnets by recycling computer hard drives versus mining the same amount of virgin material [47]. In the case considered, recycling had a human toxicity score more than 80% lower than mining and used almost 60% less energy [47]. A more recent LCA study verifies that virgin NdFeB is worse in terms of environmental impacts than its recycled counterpart [45]. However, there is as yet insufficient data available to apply these studies directly to the (H)EV industry. Even conventional RE processing environmental impacts are far from clear; needless to say, the recycling methods and other new technologies require significant research to be deemed as viable solutions.

General LCA Study Results

To introduce the idea that clean technologies and their components and recycling strategies may not be as sustainable as they seem, we provide a general overview of some of the results of various LCA studies of PMs and (H)EV motors. In terms of the life cycle production of REEs, one LCA concluded that mining and beneficiation have much lower energy and material consumption compared to other downstream stages—separation of rare earth oxides and reduction of REEs [48, 49]. However, others conclude that it is the mining and production process which is the most environmentally impactful [45, 47, 49, 29]. To examine EVs as a whole, Troy R. Hawkins' article titled, "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles," concludes that it is the production phase which exhibits the higher environmental burden [50]. Hawkins writes that the EV production phase is more environmentally intensive than that of ICEVs for all environmental impact categories with the exception of terrestrial acidification potential [50]. The study concludes that the supply chains involved in the production of electric powertrains and traction batteries add significantly to the environmental impacts of vehicle production.

Social

Socio-environmental issues have been raised in terms of rare earths used in (H)EV motors. Conditions for workers in these rare earth mining and processing facilities are not fit to cope with many health and safety measures required for the refining of this type of metals. Continue to source neodymium and other rare earth elements from China to avoid sometimes burdensome environmental regulation regarding toxic and radioactive by products [38]. All REEs cause organ damage if inhaled or ingested; some must be handled with extreme care to avoid poisoning or combustion [51, 52]. Rim et al [53] state that the whole process poses a great risk to miners and residents of mining towns who inhale higher amounts of radioactive dust.

Thorium, like any radioactive element, has its own societal implications. The fact is that in legal and regulated mining operations, the uncontrolled exposure to radioactive airborne dust is unlikely. Many mining operations already have in place safety precaution measures which effectively prevent or inhibit gamma radiation exposure via inhalation. But there are some REE mining companies operating in China that are not legal [54] and therefore could be guilty of submitting workers to gamma radiation exposure. The main concern is the inhalation of radionuclides in the thorium decay series. In the situations where radionuclide activity concentrations in the materials being handled are low; however, only in the case of bastnäsite (less than 0.02% thorium concentration), "it is important to recognize that the silica content of the airborne dust is likely to be of greater concern for occupational health than the radionuclide content" [30]. Particularly because the physical extraction and separation steps contain much more amounts of airborne metals and mineral dust.

The exposure to the general public may be more serious than those exposed in the workplace. In Malaysia, for example, several plants reported a range of 0.3 and 7.3 mBq/m^3 in activity concentration of thorium. The elevated gamma dose rates were recorded in public areas near mineral processing plants with mineral stockpiles [55]. The highest dose rates were recorded at one of the mineral piles in an area where large amounts of monazite had been deposited on the roadside at up to 2.67 µGy/h. This was 13 times the mean environmental radiation level of Malaysia [55]. The potential radiation exposure to Malaysians has created understandably a social resistance to REE mining [32]. This situation, along with the development of Lynas Advanced Materials plant in Kuantan, Malaysia led to even more "claims of environmental and social injustice."

The samarium cobalt magnet, also has a reputation for being in conflict with social welfare. Samarium cobalt was widely utilized in high-performance motors in the 1970s until civil unrest in the Democratic Republic of Congo (DRC) in 1978. Surprisingly, it was not the REE that was the bone of contention, but the cobalt. This disrupted the supply of cobalt and the price of cobalt increased 6.5 times over base price [56]. The cobalt price volatility today is not as dire, but still many companies still are hesitant to invest in or purchase cobalt, partly due to the new Dodd Frank legislation and the upcoming European Parliament proposal which is a requirement for US and European companies to certify that their products are “conflict free” with regard to the DRC [57, 58] and other conflict zones. Another more recent example of one country using its monopoly power as leverage in an economic war is China’s dispute with Japan over a fishing boat near the Senkaku Islands. During this time, China blocked rare earth shipments to Japan, for 3 weeks, which resulted in wide socio economic ramifications [59].

Social aspect of PM sustainability is also related to the illegal mining of HREEs in southern China, which used to be largely done by artisanal miners in the region. Most of the global supply of HREEs (e.g., dysprosium) originates from the “ion adsorption clay” ores of southern China. Since the HREEs are considered more strategically valuable, significant efforts have been made by Beijing to crack down on unbridled illegal mining in the region. Media reports have often attributed China’s low rare earth cost to poor environmental standards. Fearing irreversible pollution and the waste of resources caused by the rampant mining by the small rural mines, the central government in 1991 declared that ionic absorption clays in southern China would be kept under the protection of the state, and their mining, refining, and processing would be controlled by the central government. This policy, however, has never been effective. It was estimated that in 2012, illegal production of rare earths amounted to more than 40,000 tons [60]: Particularly in the case of middle and HREEs mined in southern provinces, it was estimated that 70% of the resources came from illegal mines (Fig. 4).

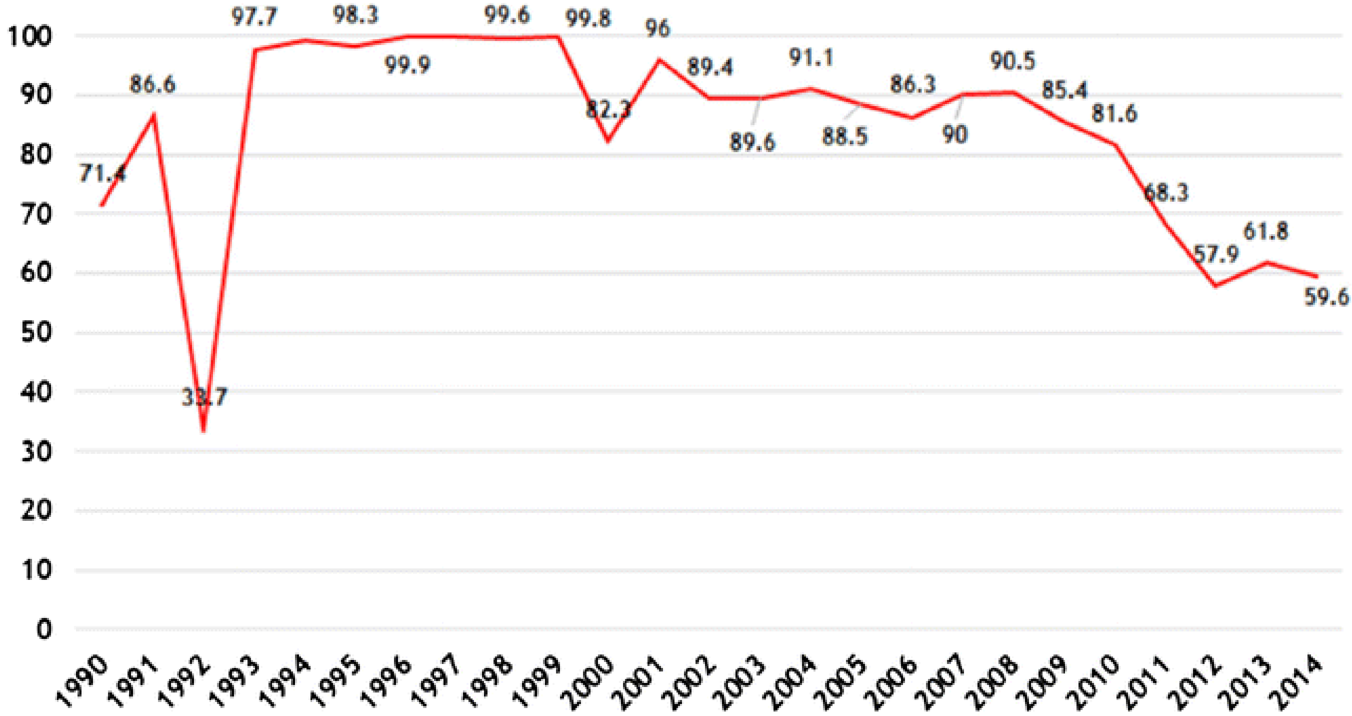


Fig. 4

Japan’s RE dependence on China (in %).

Source: Author’s calculations based on the UN Comtrade (2016). https://comtrade.un.org/data/

The social issues of the production of REEs for PM motors have been addressed above, but the consequences of the use and recycling of this motor within the (H)EV industry have yet to be illuminated. It is certainly true that the automobile industry does not have the reputation for developing sustainability. In fact, they have been accused for years as being one of the major contributors to global climate change [13]. In this report, road transport was cited as responsible for 16% of CO_2 emissions. However, with the onset of (H)EV market, the industry is contributing to a greener economy, which is a positive social consequence. Despite their associated positive social good, EVs are not a mass market, less than 1% of the automobile industry consists of EVs. But within the market, the main reason, aside from fuel cost savings, why people choose to buy EVs is because they wish to protect the environment and our health and well-being [61]. A EU government document states people perceive EVs as something healthy for the environment [62]. Social perceptions of the risk of using critical metals and dirty electricity thus need to be balanced against broader priorities toward sustainable development. As recycling and reuse technologies improve for EVs, there is less likely to be social resistance toward the PM rare earth motor, and may even become known as a green and economic product.

Economic

Currently, the main challenge in PM sustainability comes from the economic aspects, namely the price volatility of rare earth materials. The graph below evokes the EU criticality index [63], but with a focus on clean energy instead of pure economic importance to the EU. This graph demonstrates the criticality of elements such as neodymium and dysprosium, large amounts of which are used in the PMs of the (H)EV, in contrast to the relatively low risk for the batteries of (H)EVs which contain nickel. A discussion on the economic importance and price volatility of REE PMs follows.

Risk related to mineral procurement is a major issue for the automotive companies due to excessive oligopolies and an increase in resource nationalism [64]. The stable procurement of mineral resources required for production activities has become an important issue for management at the resource-using companies in developed countries as they are totally dependent on countries like China to meet their mineral demand. Therefore, the sustainable supply of these metals has a significant influence on the development of alternate energy and efficient automotive systems.

Due to this risk of obtaining critical materials, magnet manufacturers are also seeking to reduce the rare earth content of magnets while maintaining or increasing their performance. An example is Hitachi Metals who have developed magnets which reduce dysprosium content when compared to conventional NdFeB materials, reportedly without a reduction in their high temperature coercitivity [65]. According to Oliver Gutfleisch, for (H)EV motors, dysprosium partially substitutes neodymium in order to increase the coercitivity to a sufficient level [65]. The disadvantages of this are the reduction in the energy density and the exorbitant price of dysprosium [65]. While substituting REEs for other materials or even removing them completely could be seen as a possible sustainable solution, the development of a new type of motor or magnetic material may increase mining of new materials which in turn could increase environmental impacts [66] (Fig. 5).

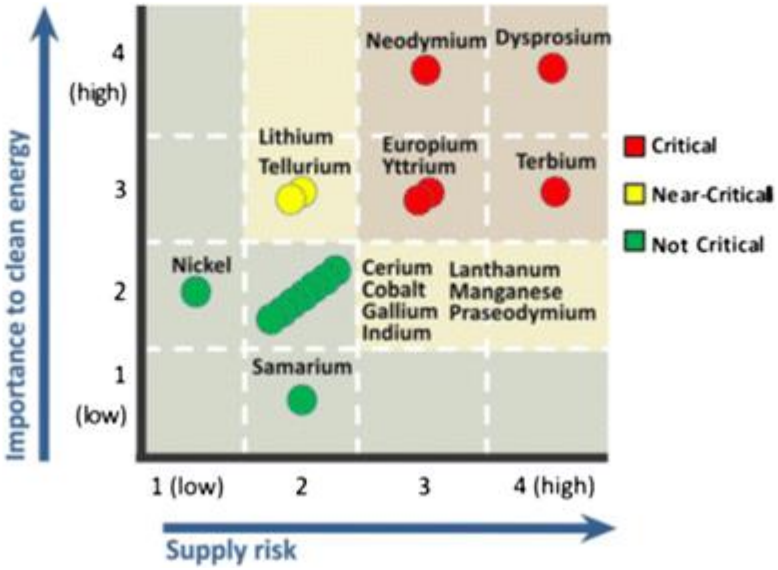


Fig. 5

Rare earth criticality and importance to clean energy.

Source: [4]

Unlike the conventional metals, rare earths are not traded at the exchange. As a result, pricing is highly obscure, and there is no way for either of the producers or consumers to hedge prices. Rare earth prices are also very affected by Chinese domestic policies as the country controls more than 90% of global supply. For example, the tightening supply policies of China caused the sharpest increase in neodymium price, which quintupled from 15 dollars in 2009 to 230 dollar per kilogram in 2011. The heavier rare earths (e.g., dysprosium, terbium, and europium) are more expensive, and historically prices have risen steadily for these elements since 2003 due to China’s rising domestic demand and escalating export controls. However, LREEs, such as lanthanum and cerium, recorded relatively modest increases of 7 and 23% during these peak periods. Tiny quantities of dysprosium can make magnets in electric motors lighter by 90%. According to a United States Energy Department report, dysprosium has become the most important element in clean energy technology [4]. Currently, 1 kg of dysprosium oxide costs around 200 USD per kilogram and 1 kg of neodymium oxide around costs 40 USD.

Rare earths fall under the classic definition of structural scarcity, meaning that unequal access to natural resources in a given society makes them scarce for large segments of the population [67]. Dysprosium is one of the most rare of the rare earths because it is not found in high concentrations and is found together with other rare earths [68]. The supply of dysprosium is elastic, and it will not be balanced with the production of other REEs. That is, mining for LREEs will not affect the dysprosium supply. For now, it is impossible to increase the production of dysprosium and at the same time maintain economic viability [4].

While the long-term price of the LREEs remains open for debate, the Chinese production quota, the region-based ad-valorem tax system, and consolidation of the industry will probably continue to tighten the supply of HREEs, such as terbium and dysprosium, keeping the prices high for these elements. The price of dysprosium oxide, used not only in hybrid vehicles but also in lasers and nuclear reactors, is projected to rise to above USD 500 in the next few years. The consolidation of RE industry and China’s clampdown on illegal mining will have a considerable impact on prices in longer terms.

The widest usage of rare earths is in PM sector, which consumes about 25–35% of total rare earths supply by quantity and more than 50% in terms of value [10]. The current applications of rare earths are divided among phosphors, ceramics, glass, and metals, with PMs representing just 23% of the volume of 130,000 tons of rare earth oxides. The most important economic application is overwhelmingly that of PMs at 38%.

If REE production faces a mountain of economic problems, then these problems look like molehills in comparison to the economic challenges posed by REE recycling. The following will review some of the recycling bottlenecks and reveal their economic and technological unfeasibility. In the automotive sector, there are no end-of-life recovery or recycling efforts in place to recover the PMs, as it is considered economically unfeasible. The problem is that many of the differing parts and components in the motor have different chemical and physical compositions making it difficult to recycle and reprocess.

According to a source around 70 or 80% of the hybrid vehicles existing are produced by Toyota Motor (Personal communication, April 24, 2016). In terms of recycling, the big difference between the EVs and the (H)EVs (Personal communication, April 8 2016) is the size of the battery and the number of motors. The Nissan Leaf, for example, is an EV so it has one motor, but a Toyota Prius hybrid has two motors. One cannot make the assumption that, because hybrid has two motors and electric has one, the hybrid uses more PMs than electric, as some hybrid vehicles function almost exactly like an EV using just one motor and some function using three motors. Not only it is technologically difficult to figure out how to remove the motor/magnets for recovery in an economic way, but it is even more difficult to know if there is enough feedstock to recycle. And if there is enough how much is needed to make recycling investments “worth it.” However, our knowledgeable source or expert, “frankly speaking, nobody knows the answer of how many vehicles will be enough (to make recycling feasible)” (Personal communication, April 24, 2016).

Despite the rather nascent commercial success of (H)EVs, there has been quite an evolution of demand. Based on certain assumptions, a study by Fulton et al. 2013 found that the combined share of all types of hybrid vehicles may reach over 75% market share in 2050, and even by 2035 they reach about 45% of global light-duty vehicles’ sales [69]. In such a scenario, this would certainly increase the demand for certain rare earths and whether the demand could be met from the existing mines *sustainably* is a relevant question to ask now. With the absence of efficient reuse and recycling or the development of technologies which use lower amounts of dysprosium and neodymium, following a path consistent with stabilization of atmospheric CO at 450 ppm might lead to an increase of approximately 700 and 2600% in the use of these two elements, respectively, over the next 25 years if their present needs in automotive and other applications are representative of the future needs [68].

The price evaluation of neodymium and dysprosium is discussed in the following: When the prices of neodymium and dysprosium spiked in 2010 and 2011, manufacturers and users worked quickly to reduce or eliminate their need for these elements in their products. In some cases, the use of the REEs was reduced or eliminated temporarily, through technological or material substitutions, but in many cases the reduction and elimination have been made semi-permanent. The industry also witnessed a dramatic reduction in demand and major importers like Japan and the US cut short their imports. Prices collapsed almost more quickly than they had risen. Unable to cope with the low prices and escalating cost, Molycorp, the major non-Chinese producer suspended its operations in August 2015. Prices are now almost at the same level as in the period of 2009.

There have been efforts made to move away from the Chinese monopoly and boost supplies of rare earths for automakers [70]. In Japan, there have been efforts to make EVs free of rare earths [71] and the government of Japan has announced that they hope to start the production of REEs from deep sea deposits in 2018 [72]. However, not all the efforts the Japanese have made have contributed positively to the reducing of the economic strain on REEs. The Japanese perpetuated an event called panic buying which occurs when companies increase their stockpiles dramatically which in turn increases prices. This economic phenomenon which occurs within the context of rare earth PM motors is the raising of prices due to perceived threats and was explored extensively in [73]. During the 2010 REE crisis, some Japanese companies forced their suppliers to increase their stockpiles of rare earths at the very moment the prices were highest and the materials were hardest to obtain [73]. Moreover, the enormous price jumps in 2012 (Figs. 6, 7) are thought to be caused by speculators [73]. The (H)EV industry could not afford to rely on rare earths due to these economic uncertainties (Fig. 8).

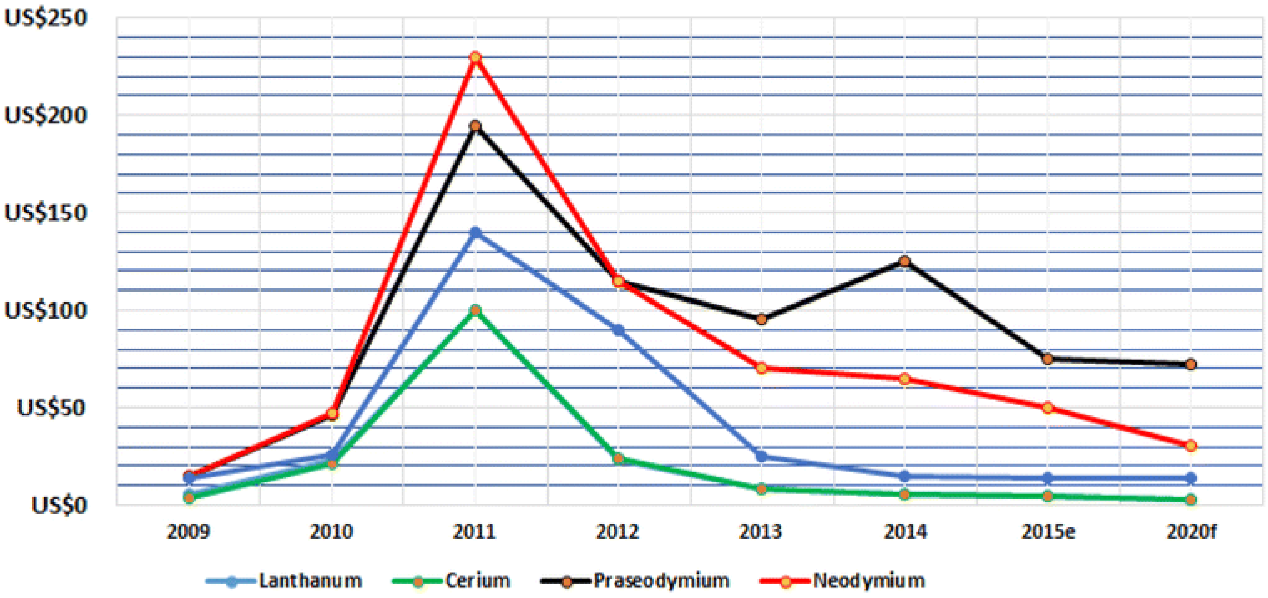


Fig. 6

Rare earth oxide prices—LREEs (USD per kilogram)

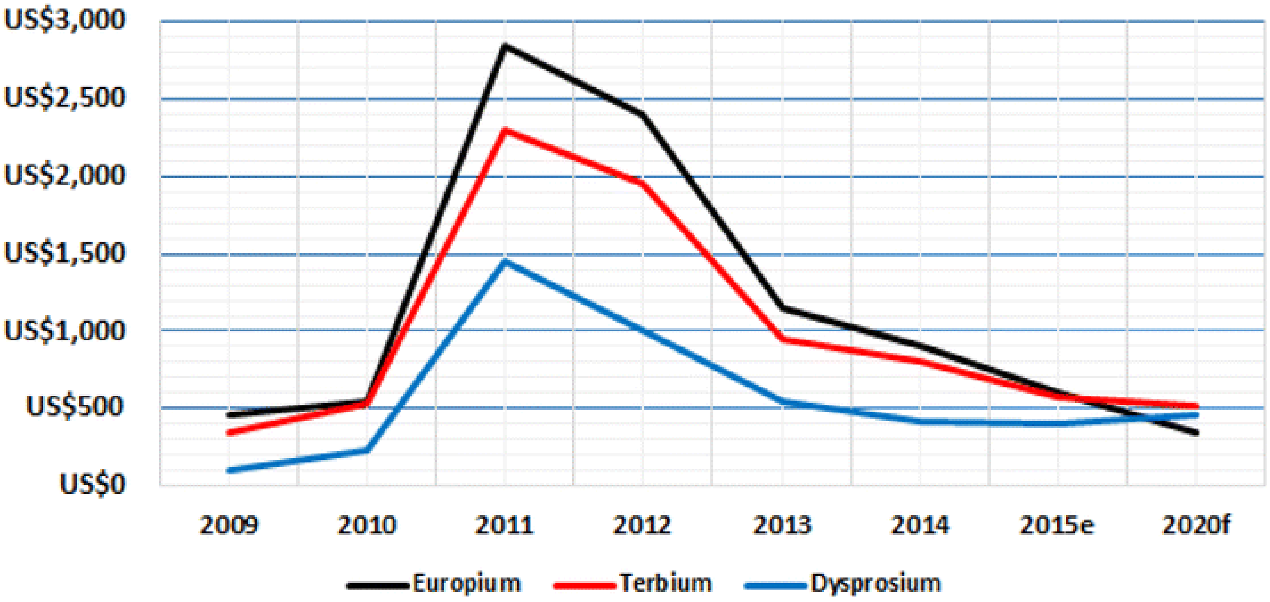


Fig. 7

Rare earth oxide prices—HREEs (USD per kilogram).

Metal Pages (2016). Argus Media private limited London. http://www.metal-pages.com/metalprices/rareearths/

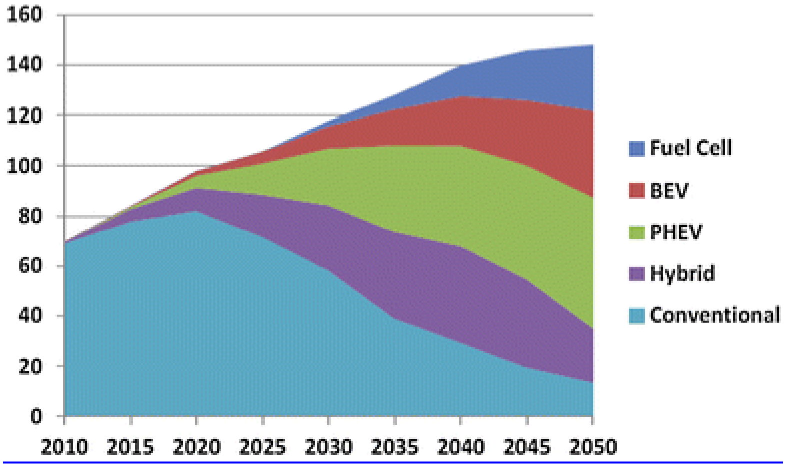


Fig. 8

Automotive technology evolution.

Source: [69]

Another economic anomaly in reference to REEs is called the balance problem [74, 75]. Simply put, there is an abundance of certain REEs in the mixed RE ores, and a serious lack of others and the ones which are not abundant in nature are those which are the most in demand. The ideal economic balance would be that the supply and demand of REEs were equal. However, within (H)EVs, there is a greater need for HREEs such as dysprosium, for example, than lighter REEs such as cerium. The balance problem implies perhaps the EV industry should help to find new ways to use all types of REEs. However, the adoption of a substitute may lead to competitive situations for the material’s original use: For example, if one substituted terbium in place of dysprosium in (H)EV PMs, it could have a boomerang effect in the availability and price of terbium which is used in LED lighting [76].

Technical

Geopolitical- or economy-related developments often bring technological change in the market. Global PM industry has a long history of technological developments. Over the last 50 years or so, PMs have evolved through four generations of technologies. Figure 9 shows the evolution of these magnets [14]. Aluminum nickel cobalt (AlNiCo) magnets have been replaced by hard ferrites. These in turn have been replaced by the superior samarium cobalt (SmCo) rare earth magnets. In response to the perceived shortfall of cobalt due to conflict in the Congo and Cold War politics surrounding Soviet Union (another leading cobalt producer of that time), companies in the US and Japan developed the NdFeB magnets in late 1970s. This magnet has been currently the dominant technology ever since.

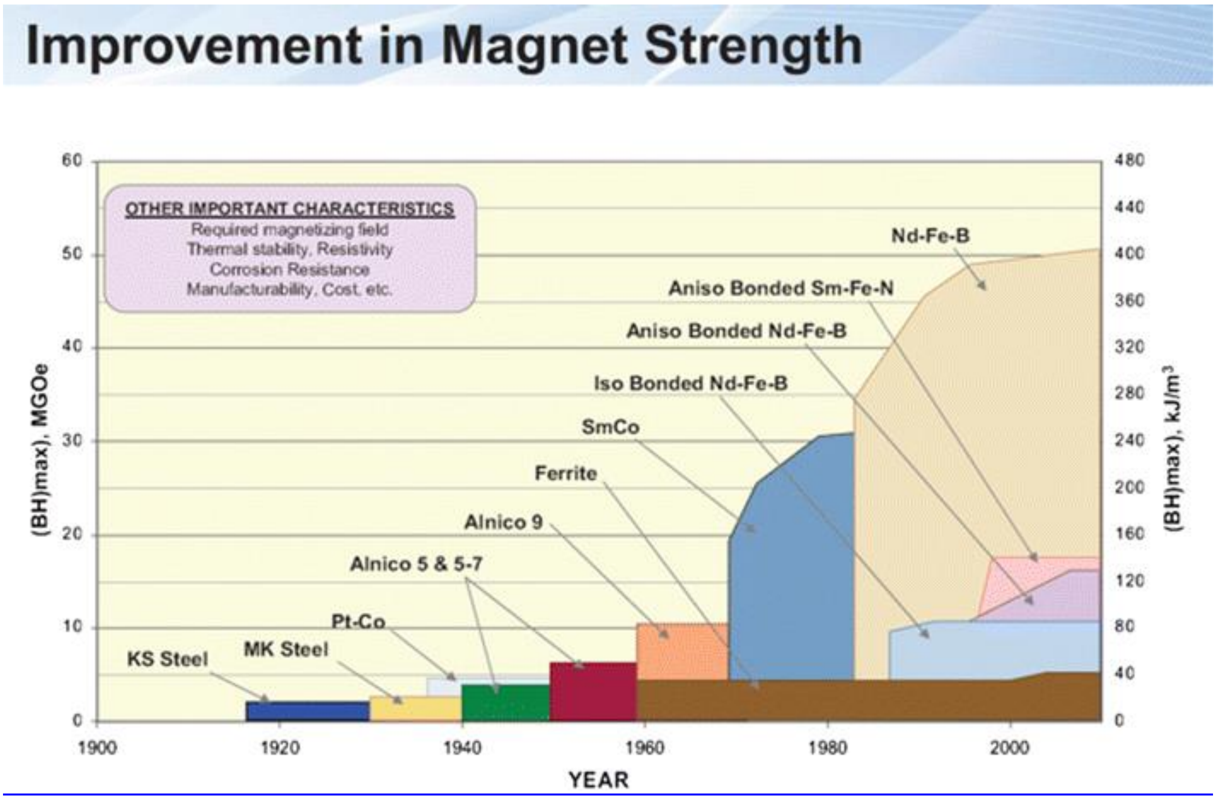


Fig. 9

Evolution of permanent magnets and their strengths.

Source: [9, 14]

The performance of the motor largely depends on the quality of the magnets used. The high-performance motors use rare earth magnets containing NdFeB, which offers by far the highest energy density for EVs [23]. A partial substitution of neodymium by dysprosium enables the use of these PMs even at higher temperatures, which is especially important for use in electric motors. However, instead of adding dysprosium, which is an expensive and a critical HREE, one could easily substitute the NdFeB magnet with SmCo. Replacing the rare earth PMs with ferrite magnets or AlNiCo is not really possible due to the enhanced risk of demagnetization.

At present, there are only two main types of motors used in EVs—the IM and the PM. PM motors are more widely used in automotive companies such as Toyota, Nissan, and BMW. The IM is used by EV manufacturers like Tesla. There are many specifications for a PM motor such as being able to operate under relatively high temperatures, and a high BHmax and flux output. The PM motor has high torque and high power density, and therefore, like PMs over ferrite magnets, PMs can perform at the same level while utilizing less space. The PM motor could be viewed as more efficient than even the Tesla IM in that the PM motor saves energy required for cooling due to less heat loss in the motor. The lower weight of the PM motor, by 40%, results in saving on fuel [77].

The PM motor presents some obvious advantages over the IM in these aspects. But the IM has some compelling advantages, too. The biggest advantage might be that it does not contain any rare earth PMs. The second is that the cost of Tesla IM motor is quite low compared to a Nissan Leaf PM motor. According to the International Copper Association, a PM motor costs an estimated $260–$590 and an IM motor costs around $200 [77]. Lastly, PM motor has a complex control strategy and needs more maintenance than IM. Overall, the design of IMs is simpler than PM motors and thus costs less and their recycling is potentially easier [78].

While the Tesla IM seems to garner a ‘green’ image, the contribution of its motor to sustainability is not so clear. Because the PM motor can power a car with less material (and weighing 40% less), one could argue that the PM motor has a smaller emission load as well. More evidence for the sustainability and efficiency of PM motor can be seen in its magnetic flux. The current (energy) in any motor can be divided into two types: magnetizing current (flux) and the current producing torque [39]. In IM, both the currents (flux) come from the supply, meaning the battery. In PM motors, the magnets provide magnetization in the motor and hence the motor needs less current than IM to produce the same torque which means less copper losses (Personal communication, December 11, 2016) [79]. PM motors are undoubtedly more efficient than the IM given the same size of the motor [77]. Nevertheless, it cannot be claimed that the Nissan Leaf’s PM motor is more sustainable than Tesla’s IM motor, because the efficiency of the motor can vary with speed, size, and power output. All in all, an IM, which is the same *size* as a PM motor, will always have a lower efficiency compared with PM motors.

In the previous sections, the challenges with regard to economic viability and environmental and social aspects of introducing REE-based motors have been discussed. It is clear that the way forward also implies many technological challenges. Dismantling these motors from (H)EVs in an automatic or systemized manner is currently not possible. Although there has been some research into developing dismantling features in LCD TVs and laptops [80, 81], none have been developed for (H)EVs. Moreover, the placement of the motor and the position of the rare earth magnets inside are not convenient for removal. To give more detail on why these motors have magnets not designed for easy removal, we turn again to our expert source explains that if we try to generate a large amount of torque by using a small, lightweight motor, then we have to increase the number of rpm (rotations per minute) and transform it to torque. However, if we try to increase the rpm of motor, then this causes the motor to have a lot of a vibration. Therefore, one must use a strong material to fix the magnet inside the motor. Thus, the increased rpm and the material make it difficult to remove the magnet from the motor (Personal communication, April 24, 2016). And to make matters worse, the placement of these magnets is different in almost *every* vehicle model, no matter if they share the same brand, make, and model.

Automotive industries seem to be actively working on researching and developing dismantling and recycling techniques and incorporating them in vehicle designs. Toyota established the Automobile Recycle Technical Center within Toyota Metal Co., Ltd. in 2001 in order to look at “dismantling technologies for the magnets used in devices such as hybrid vehicle drive motors which use neodymium and dysprosium” [82]. Toyota is taking a two-fold approach that many car companies are following: (1) use less rare earths when possible and (2) procure rare earths from recycled motors or urban mines. Unfortunately, to date, it has been proven that there is no constructive method for recycling the rare earths in these powerful magnets.

One of the most reliable recycling method for REE PMs was developed by the University of Birmingham in [83]. It was a major breakthrough because it allowed one to apply hydrogen to a used PM from a motor which turned into a rare earth oxide powder in a matter of minutes [83]. The issue here is that the quality diminishes each time the material is decrepitated. The nickel coating, which covers the magnet in a Ni–Cu–Ni layer, is often the cause of the recycling barrier. Because of these technical bottlenecks, there are still no commercial recycling processes available. The hydrogen decrepitation process is one of the most feasible recycling techniques to date in terms of environmental and economic cost, because it allows one to use as little energy and chemicals as possible to recover the neodymium and let the hydrogen do the hard work (data from Dr. Vicky Mann's presentation ‘‘Magnetic Materials Group (MMG) Recycling of Rare Earth (NdFeB) Magnets", within the NMP2-SE-2012-310240 REMENANCE project) [84]. Also, the powder needs to be handled in an inert protective atmosphere due to its high reactivity with oxygen (Personal communication, Enrique Herrariz, April, 2016).

Discussion

The techniques for determining whether PM motors are sustainable or not are not precise. However, this type of assessment (like many sustainability assessments) of PM motors sheds light on a shadowy aspect of the (H)EV industry. Unfortunately, many of the industry-sponsored studies and publications contain data which are sensitive and sometimes confidential and therefore only viewable in a highly aggregated format. This is another reason why it is important to carry out a sustainability assessment of a small component of (H)EVs of such a large (automotive) industry. Performing environmental impact assessments which are released to the public is one way to increase accountability and social aspects. If there was an association or open line of communication between the auto industry and the PM manufacturers, then the opportunities for increasing knowledge share and sustainable measures would increase. Currently, there is no global association existing to facilitate exchange between the manufacturers, post-processors, and recyclers of these motors. By focusing on the aspect of (H)EV motor production and manufacturing, and not just use phase, which is what the auto industry tends to focus on, it is possible to communicate, in a concise manner, the gains (and losses) in the sustainable development of a rare earth PM motor.

The authors venture to explain different methods on how to bypass the sustainability constraints of PM motors. The sociopolitical decisions made by the rare earth and HEV industry so far do not reflect the upmost sustainable values. For example, the decision for the rest of the world to sit on the sidelines while China took over was convenient for a short period but proved near-sighted and has evidently become less and less durable as time passes. Furthermore, the (H)EV industry continues to source these magnets for their motors, letting China take the "environmental" hit. If the West decides again to take up the large-scale mining and pre-processing of these magnets, then sustainable actions could be implemented more easily, but always at a cost. Sustainability recognizes that both extremely high and extremely low costs are not lasting and are inherently unsustainable.

Sustainability also recognizes the social and economic need to mine and emit harmful substances, but in an accountable and open manner. This is the concept of responsible mining, and involves all the four pillars of sustainability addressed in this review. Sustainability for the PM motor supply chain would mean employing advanced technological improvements advanced technological improvements such as scrubbers for smelters and environmental, health and safety monitoring system for employees at all stages of manufacturing and dismantling, all for a fair price. But the economics has not worked out for Chinese producers to be able to do this. The sustainable automotive and REE industries are intertwined and dependent on each other. Thus, they must work together and rely on each other to ensure a sustainable value chain. The rare earth industry is needed to create an environmentally friendly transportation sector, with neodymium and other REEs needed in large quantities if the electric car revolution will succeed in removing combustion engines from the automotive industry. On the other hand, the (H)EV industry needs to be held accountable for sourcing their magnets responsibly.

Conclusions

These cross cutting pillars of sustainability—environmental, economic, social, and technical—have differing conclusions regarding the permanent rare earth magnet motor in the (H)EV industry, which shows the need for the automobile industry to come up with strict results (using LCA, cost–benefit analysis, etc.). The conclusion of the environmental assessment is that PMs are not sustainable and are performing poorly in terms of overall 'greenness.' The conclusion of the economic assessment is that the HREEs are the most costly part of a PM motor and more effort should be done to source the LREEs. The social assessment shows that PMs can induce geopolitical strife and cause health problems for the communities where they are extracted and processed. The technical assessment states that technologies for producing PMs and recycling of PM motors need to be developed in order for them to be considered sustainable.

We recommend that the (H)EV industry take heed of this sustainability assessment, but recognize that a sustainability assessment can often have conflicting results. For instance, if the sociopolitical assessment concludes a need for material substitution in order to combat monopolies and criticality, then this approach is not necessarily a sustainable solution for the environment. Alexander King in a conference paper states this is because increased mining may "increase environmental impacts and spread them to new locations," and the development of a new magnetic material will threaten the research which is going into putting a recycling solution in place [66]. The right conclusion is clearly not to write off the concept of EVs or PM motors for that matter. Rather, a good conclusion might be to acknowledge the inherent attractiveness of the EV target state while also acknowledging the innovative opportunity to increase the knowledge of recycling processes for these rare earth motors. The intention of this paper is meant to have sharply defined what needs to be known in order to make the PM motor and its industry practices more sustainable.

We conclude that the sustainability of these PM motors will be largely dependent on the following aspects: improved recovery and recycling methods of these magnets from automobile sector, acceptable alternative propulsion technologies, continued price stability and availability of critical REEs, cost to produce (H)EVs, and improvement in communication within the value chain. Other aspects mentioned by King include "technology substitution at the system level as opposed to the material level, that is, using heat engines in place of electric motors, or a new type of motor in place of permanent magnet motors. The future of sustainable transportation hinges on the development of the aforementioned approaches. The four pillar paradigm examined in this paper reveals how a sustainable technology has developed and currently subsists unsustainably.

Acknowledgements

The research by Nabeel Mancheri was funded by the European Commission's Marie Curie Actions, Grant No. 656998. The research by Gwendolyn Bailey was funded by the European Union's EU Framework Programme for Research and Innovation Horizon 2020
under Grant Agreement No. 674973. The research was supported by KU Leuven Departement

Industriele Ingienieurswetenchappen, Oude Markt 13,3000 Leuven (Faculty of Engineering Technology). The authors would also like to recognize and thank the following persons for their contribution toward the technical section of this paper: Awais Ikram, Amit Jha, and Pranshu Upadhayay.

References

1. 1.

Bourzac K (2011) The rare-earth crisis. MIT Technol Rev 114(3):58–63Google Scholar

2. 2.

Yap C-W (2015) China ends rare-earth minerals export quotas. Wall Street Journal. Available at: https://www.wsj.com/articles/china-ends-rare-earth-minerals-export-quotas-1420441285. Accessed 5 March 2017

3. 3.

Han-Wei L, John M (2012) China's Rare Earths Export Quotas: Out of the China-Raw Materials Gate, But Past the WTO's Finish Line?. J Int Economic Law 15 (4): 971-1005. doi: 10.1093/jiel/jgs037

4. 4.

Bauer D, Diamond D, Li J, Sandalow D, Telleen P, Wanner B (2011) U.S. Department of Energy, Advanced Research Projects Agency, Energy Critical materials strategy. United States. doi: 10.2172/1000846

5. 5.

Abraham DS (2015) The war over the periodic table. Bloomberg View. Available at: https://www.bloomberg.com/view/articles/2015-10-23/the-war-over-the-periodic-table. Accessed 5 March 2017

6. 6.

Financial Times (2011) EU stockpiles rare earths as tensions with China rise. [online]. Available at: http://business.financialpost.com/investing/eu-stockpiles-rare-earths-as-tensions-with-china-rise. Accessed 6 Feb 2017

7. 7.

Harman A (2012) Honda rare-earth recycling may avoid China Export Flap. WardsAuto. http://wardsauto.com/industry/honda-rare-earth-recycling-may-avoid-china-export-flap. Accessed 25 April 2016

8. 8.

Golev A, Scott M, Erskine PD, Ali SH, Ballantyne GR (2014) Rare earths supply chains: current status, constraints and opportunities. Resour Policy 41:52–59. doi: 10.1016/j.resourpol.2014.03.004CrossRefGoogle Scholar

9. 9.

Constantinides S (2016) Market Outlook for Ferrite, Rare Earth and Other Permanent Magnets: 2015 to 2025. In: The magnetics 2016 meeting was held Jan. 21-22, 2016 in Jacksonville, FL.Google Scholar

10. 10.

Humphries M (2013) Rare earth elements: the global supply chain. In: CRS Report for Congress. Congressional Research Service. Washington, DCGoogle Scholar

11. 11.

Els F (2013) Honda's starts recycling program to extract 80% of rare earths from used hybrid batteries. Available from: http://www.mining.com/hondas-starts-recycling-program-to-extract-80-of-rare-earths-from-used-hybrid-batteries-43719/. Accessed 7 Nov 2016

12. 12.

Environmentally Friendly Vehicles (2012) Environmentally friendly vehicles and the world forum for the harmonization of vehicle regulations (WP. 29). Representatives of India and USAGoogle Scholar

13. 13.

Mock P (2015) European vehicle market statistics. Available from: http://eupocketbook.theicct.org. Accessed 6 April 2016

14. 14.

Shaw S (2012) Permanent magnets: the demand for rare earths. In: 8th international rare earths conference, Arnold Magnetic Technologies, Hong KongGoogle Scholar

15. 15.

Moore K (2015) Is the automobile industry driving away from REE motors. In: North America rare earth conference, Las VegasGoogle Scholar

16. 16.

Association EAM (2015) ACEA Position Paper: The COP21 climate change conference 2015, BrusselsGoogle Scholar

17. 17.

Devuyst D (2000) Linking impact assessment and sustainable development at the local level: the introduction of sustainability assessment systems. Sustain Dev 8(2):67–78CrossRefGoogle Scholar

18. 18.

Hickman L (2012) Are electric cars bad for the environment. The Guardian. https://www.theguardian.com/environment/blog/2012/oct/05/electric-cars-emissions-bad-environment. Accessed 25 April 2016

19. 19.

Kingsnorth D (2012) The rare earth industry: a delicate balancing act. In: Technology metals summit, TorontoGoogle Scholar

20. 20.

Widmer JD, Martin R, Kimiabeigi M (2015) Electric vehicle traction motors without rare earth magnets. Sustain Mater Technol 3:7–13. doi: 10.1016/j.susmat.2015.02.001Google Scholar

21. 21.

Schulze R, Buchert M (2016) Estimates of global REE recycling potentials from NdFeB magnet material. Resour Conserv Recycl 113:12–27. doi: 10.1016/j.resconrec.2016.05.004CrossRefGoogle Scholar

22. 22.

McLellan BC et al (2016) Sustainability of the rare earths industry. Procedia Environmental Sciences 20:280–287Google Scholar

23. 23.

Ford (2014) Ford sustainabilty report 13-14Google Scholar

24. 24.

Yang XJ, Lin A, Li X-L, Wu Y, Zhou W, Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environ Dev 8:131–136. doi: 10.1016/j.envdev.2013.03.006CrossRefGoogle Scholar

25. 25.

Li L, Yang X (2014) China's rare earth ore deposits and beneficiation techniques. In: European Rare Earth Resource Conference.Google Scholar

26. 26.

Lee JCK, Wen Z (2016) Rare earths from mines to metals: comparing environmental impacts from China's main production pathways. J Ind Ecol. doi: 10.1111/jiec.12491

27. 27.

Weng, Z, Haque N, Mudd, GM, Jowitt SM (2016) Assessing the energy requirements and global warming potential of the production of rare earth elements. J Clean Prod 139:1282–1297Google Scholar

28. 28.

Wang Y, Wu P, Wang P, Chen N, Zhang Y, Ma X, Yue H, Peng S (2014) The emission standard of rare industrial pollutant task group. J Safe Environ. doi: 10.13637/j.issn.1009.6094.2014.04.056

29. 29.

Koltun P, Tharumarajah A (2014) Life cycle impact of rare earth elements. ISRN Metall 2014:907536. doi: 10.1155/2014/907536

30. 30.

Agency IAE (2011) Radiation protection and norm residue management in the production of rare earths from thorium containing minerals, in safety report series. International Atomic Energy Agency, ViennaGoogle Scholar

31. 31.

Kaiman J (2014) Rare earth mining in China: the bleak social and environmental costs. The Guardian. Available at: https://www.theguardian.com/sustainable-business/rare-earth-mining-china-social-environmental-costs. Accessed 5 March 2017

32. 32.

Ali SH (2014) Social and environmental impact of the rare earth industries. Sustainability 3:123–134. doi: 10.3390/resources3010123Google Scholar

33. 33.

British Broadcasting Company (2014) Elements. In: Rowlatt J (ed) Rare earth elements (Ce, Nd, Dy, Er, etc). http://www.bbc.co.uk/programmes/p02rnvf2. Accessed 31 August 2016

34. 34.

Qi Z (2011) Rare earths to be more tightly controlled. In: China Daily Europe, Beijing. http://europe.chinadaily.com.cn/china/2011-03/08/content_12133351.html. Accessed 25 April 2016

35. 35.

Juan D (2012) Green priority for rare earths. In: China Daily Europe. http://europe.chinadaily.com.cn/business/2012-06/21/content_15516454.htm. Accessed 25 April 2016

36. 36.

Sprecher B et al (2014) Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. Environ Sci Technol 48(7):3951–3958. doi: 10.1021/es404596qCrossRefGoogle Scholar

37. 37.

Stenquist P (2012) How green are electric cars? Depends on where you plug in. The New York Times. http://www.nytimes.com/2012/04/15/automobiles/how-green-are-electric-cars-depends-on-where-you-plug-in.html. Accessed 11 November 2016

38. 38.

Don Anair AM (2012) State of charge: electric vehicles' global warming emissions and fuel-cost savings across the United States. Union of Concerned Scientists, CambridgeGoogle Scholar

39. 39.

Pellegrino G, Vagati a, Boazzo B, Guglielmi P (2012) Comparison of induction and PM synchronous motor drives for EV application including design examples. IEEE Trans Ind Appl 48(6):2322–2332CrossRefGoogle Scholar

40. 40.

Jha A (2010) Electric cars cannot cut CO_2 emissions on their own, warn engineers. The Guardian. https://www.theguardian.com/environment/2010/may/25/electric-cars-carbon-emissions. Accessed 11 November 2016

41. 41.

Binnemans K, Jones PT, Blanpain B, Van Gerven T, Yang Y, Buchert WM (2013) J Clean Prod 51:29–38. doi: 10.1016/j.jclepro.2012.12.037

42. 42.

Dent PC (2012) Rare earth elements and permanent magnets (invited). J Appl Phys 111(7):07A721. doi: 10.1063/1.3676616CrossRefGoogle Scholar

43. 43.

Recycling Permanent Magnets In One Go". Fraunhofer-Gesellschaft. N.p., 2017. Web. 7 Feb. 2017. https://www.fraunhofer.de/en/press/research-news/2015/september/recycling-permanent-magnets-in-one-go.html. Accessed 11 November 2016

44. 44.

Magnetic idea: Rare-earth recycling." Department of Energy Pulse. Number 377.http://web.ornl.gov/info/news/pulse/no377/story3.shtml. Accessed 11 November 2016

45. 45.

Jin H, Afiuny P, McIntyre T, Yih Y, Sutherland JW (2016) Comparative life cycle assessment of NdFeB magnets: virgin production versus magnet-to-magnet recycling. Proc CIRP 48:45–50CrossRefGoogle Scholar

46. 46.

Sprecher B, Kleijn R, Kramer GJ (2014) Recycling potential of neodymium: the case of computer hard disk drives. Environ Sci Technol 48(16):9506–9513. doi: 10.1021/es501572zCrossRefGoogle Scholar

47. 47.

Sprecher B (2014) Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets—supporting information. Environ Sci Technol 48(7):3951–3958. doi: 10.1021/es404596qCrossRefGoogle Scholar

48. 48.

Tharumarajah A, Koltun P (2011) Cradle to gate assessment of environmental impact of rare earth metals. In: 7th Australian conference on life cycle assessment. Australian Life Cycle Assessment Society, Melbourne. https://publications.csiro.au/rpr/pub?list=BRO&pid=csiro:EP124364&sb=RECENT&n=44&rpp=50&page=81&tr=5035&dr=all&dc4.browseYear=2011. Accessed 25 August 2016

49. 49.

Navarro J (2015) Environmental Evaluation of Rare Earth Elements: Processing, Products, and Pathways. https://search.proquest.com/docview/1729568731?accountid=17215. Accessed 16 November 2016

50. 50.

Hawkins TR et al (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):53–64. doi: 10.1111/j.1530-9290.2012.00532.xCrossRefGoogle Scholar

51. 51.

Kemakta Konsult AB (2014) Geological Survey of Finland Institute of Geology & Mineral Exploration Health and safety issues in REE mining and processing An internal EURARE guidance report. Available at: http://www.eurare.eu/docs/internalGuidanceReport. Accessed 6 February 2017

52. 52.

Kiggins, RD (ed) (2015) The political economy of rare earth elements: rising powers and technological change. Palgrave Macmillan UKGoogle Scholar

53. 53.

Rim KT, Koo KH, Park, JS (2013) Toxicological evaluations of rare earths and their health impacts to workers: a literature review. Saf Health Work 4(1):12–26CrossRefGoogle Scholar

54. 54.

Mancheri NA (2012) China's white paper on rare earths. East Asia Forum 2012. Available from: http://www.eastasiaforum.org/2012/08/16/chinas-white-paper-on-rare-earths/. Accessed 23 Oct 2016

55. 55.

Omar M, Hassan A, Sulaiman I (2006) Radiation exposure during travelling in Malaysia. Radiat Prot Dosimetry 121(4):456–460. doi: 10.1093/rpd/ncl060CrossRefGoogle Scholar

56. 56.

Constantinides S (2016) Permanent magnets in a changing world market. Magnetics Business & Technology, Arnold Magnetic TechonolgiesGoogle Scholar

57. 57.

European Parliament (2017) Conflict minerals: MEPs secure mandatory due diligence for importers. Available at: http://www.europarl.europa.eu/pdfs/news/expert/infopress/20161122IPR52536/20161122IPR52536_en. Accessed 6 February 2017

58. 58.

China's global quest for resources and implications for the United States (2012). In: United States-China Economic and Security Review Commission, Washington, DC. http://origin.www.uscc.gov/sites/default/files/transcripts/1.26.12HearingTranscript.pdf. Accessed 25 November 2016

59. 59.

Blakely CC, Joseph, Khaitan A, Sincer I, Williams R (2016) Rare earth metals & China. Available from: <http://sites.fordschool.umich.edu/china-policy/files/2012/09/Rare-Earth-Metals-China.pdf>. Accessed 7 April 2016

60. 60.

Packey DJ, Kingsnorth D (2016) The impact of unregulated ionic clay rare earth mining in China. Resour Policy 48:112–116. doi: 10.1016/j.resourpol.2016.03.003CrossRefGoogle Scholar

61. 61.

Ultra Low Emission Vehicles (2015) Uptake of ultra low emission vehicles in the UK: a rapid evidence assessment for the Department for Transport. https://www.gov.uk/government/publications/ultra-low-emission-vehicles-evidence-reviewof-uptake-in-the-uk. Accessed 20 July 2016

62. 62.

Science for Environment Policy: European Commission DG Environment News Alert Service, edited by SCU, The University of the West of England, Bristol.Google Scholar

63. 63.

European Commission (2011) Critical raw materials for the EU, Report of the Ad-hoc Working Group on defining critical raw materialsGoogle Scholar

64. 64.

Mancheri NA, Marukawa T (2016) Rare earth elements: China and Japan in industry, trade and value Chain. ISS Contemporary Chinese ResearchGoogle Scholar

65. 65.

Gutfleisch O et al (2011) Magnetic materials and devices for the 21st century: stronger, lighter, and more energy efficient. Adv Mater 23(7):821–842. doi: 10.1002/adma.201002180CrossRefGoogle Scholar

66. 66.

King AH (2016) When agendas align: critical materials and green electronics. In: Electronics goes green 2016+ International Congress, Berlin. https://www.electronicsgoesgreen.ISBN978-3-00-053763-9org6. Accessed 14 October 2016

67. 67.

Bingham Kennedy J (2001) Environmental scarcity and the outbreak of conflict. Available from: http://www.prb.org/Publications/Articles/2001/EnvironmentalScarcityandtheOutbreakofConflict.aspx. Accessed 7 Nov 2016

68. 68.

Alonso E, Sherman AM, Wallington TJ, Everson MP, Field FR, Roth R, Kirchain RE (2012) Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ Sci Technol 46(8):4684. doi: 10.1021/es203518dCrossRefGoogle Scholar

69. 69.

Fulton L, Lah O, Cuenot F (2013) Transport pathways for light duty vehicles: towards a 2° scenario. Sustainability 5(5):1863–1874. doi: 10.3390/su5051863CrossRefGoogle Scholar

70. 70.

Mancheri NA (2012) Chinese monopoly in rare earth elements: supply-demand and industrial applications. China Report Nov 48:449–468CrossRefGoogle Scholar

71. 71.

Phys Org (2010) Japan develops vehicle motor free of rare earths. https://phys.org/news/2010-09-japan-vehicle-motor-free-rare.html. Accessed 1 June 2016

72. 72.

Government of Japan (2013) Basic plan of ocean policy. TokyoGoogle Scholar

73. 73.

Sprecher B et al (2015) Framework for resilience in material supply chains, with a case study from the 2010 rare Earth crisis. Environ Sci Technol 49(11):6740–6750. doi: 10.1021/acs.est.5b00206CrossRefGoogle Scholar

74. 74.

Binnemans K, Jones PT, Van Acker K, Blanpain B, Mishra B, Apelian D (2013) Rare-earth economics: the Balance Problem. JOM 65:846–848. doi: 10.1007/s11837-013-0639-7

75. 75.

Binnemans K, Jones PT (2015) Rare Earths and the Balance Problem. J Sustain Metall 1:29–38. doi: 10.1007/s40831-014-0005-1

76. 76.

Zepf V, Reller A, Rennie C, Ashfield M, Simmons J (2014) Materials Critical to the Energy Industry. An Introduction, 2nd edition. BP P.L.C., London. http://www.bp.com/content/dam/bp/pdf/sustainability/group-reports/ESC_Materials_handbook_BP_Apr2014.pdf. Accessed 25 April 2016

77. 77.

International Copper Association (2013) Performance/cost comparison of induction-motor & permanent-magnet-motor in a hybrid electric car. http://www.coppermotor.com/wp-content/uploads/2013/08/Techno-Frontier-2013-MBurwell-ICA-EV-Traction-Motor-Comparison-v1.8-Eng1.pdf. Accessed 15 October 2016

78. 78.

Nanada G, Kar NC (2006) A survey and comparison of characteristics of motor drive used in Electric Vehicles. In: Canadian conference on electrical and computer engineering, OttawaGoogle Scholar

79. 79.

Yildirim M, Polat M, Kürüm H (2014) A survey on comparison of electric motor types and drives used for electric vehicles. In: 16th international power electronics and motion control conference and exposition, AntalyGoogle Scholar

80. 80.

Peeters JR et al (2012) Active disassembly for the end-of-life treatment of flat screen televisions: challenges and opportunities. In: Matsumoto M et al (eds) Design for Innovative value towards a sustainable society: proceedings of EcoDesign 2011: 7th international symposium on environmentally conscious design and inverse manufacturing. Springer, Dordrecht, pp 535–540Google Scholar

81. 81.

Peeters JR (2013) Effects of boundary conditions on the end-of-life treatment of LCD TVs. CIRP Ann Manuf Technol 62(1):35–38CrossRefGoogle Scholar

82. 82.

Vehicle Recycling (2014) Toyota Motors Corporation, Toyota City, Aichi Prefecture, Japan. http://www.toyota-global.com/sustainability/report/vehicle_recycling/pdf/vr_all.pdf. Accessed 03 May 2016

83. 83.

Harris IR, Williams A, Walton A, Speight J (2014) Magnet recycling. Google Patents. https://www.google.com/patents/US8734714. Accessed 30 April 2016

84. 84.

Mann, V (2012) Recycling of Rare Earth (NdFeb) Magnets. University of Birmingham. PresentationGoogle Scholar