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THEMATIC SECTION: GREEN RARE EARTH ELEMENTS–INNOVATIONS IN ORE PROCESSING, HYDROMETALLURGY, AND ELECTROLYSIS

Recycling of NdFeB Magnets from Electric Drive Motors of (Hybrid) Electric Vehicles

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Abstract (Hybrid) electric vehicles are assumed to play a major role in future mobility concepts. Although sales numbers are increasing, little emphasis has been laid on the recycling of some key components such as power electronics or electric motors. Permanent magnet synchronous motors contain considerable amounts of rare earth elements that cannot be recovered in conventional recycling routes. Although their recycling could have large economic, environmental, and strategic advantages, no industrial recycling for permanent magnets is available in western countries at the moment. Regarding the essential steps, dismantling of electric vehicles as well as the extraction of magnets from the rotors, little has been published before. This paper therefore presents and discusses different recycling approaches for the recycling of NdFeB magnets from (hybrid) electric vehicles. Many results stem from the German research project "Recycling of components and strategic metals of electric drive motors."

Keywords NdFeB magnets · Electric motor · Electric vehicle · Hybrid electric vehicle · Recycling · Rare earth elements

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Introduction

Due to the impression of peak oil, the accelerated urbanization of the world, and the effort to reduce greenhouse gases, electromobility has been promoted by companies and governments in the last decade. At the moment, electromobility in the forms of pure electric vehicles (EVs) and hybrid electric vehicles (HEVs) is presumed to gain considerably in importance during this century [1]. For (H)EVs and similar applications like electric bicycles, large growth rates can already be observed today [2]. The main growth-blocking issues, i.e., price, range, and charging infrastructure, are currently addressed. Some companies, such as General Motors and Tesla, aim at a breakthrough for EVs by the introduction of affordable mass-produced EVs (35,000 US$) with acceptable ranges in 2017 [3].

Table 1 gives an overview of the (H)EV market in the USA, the EU, and China in 2015 as well as applied motorization types. The most important motor types in commercially available (H)EVs are the induction or asynchronous motor (IN) and the permanent magnet (PM) synchronous motor [20, 21]. Although IN motor-driven EVs, represented mainly by Tesla Model S and Zotye Z100/Cloud, have gained in importance, PM motor configurations continue to dominate. IN motors were introduced as a cheaper and magnet-free alternative to PM motors over the last few years, but do not reach as high power densities and efficiencies as PM motors [7, 20]. The costs of PM motors are estimated to be 30–200 % above the costs for IN motors of the same power depending on the prices of rare earth elements (REEs) [22, 23]. Due to the limited space in HEVs and the general interest in lightweight construction, currently, PM motors are the

Table 1 Electric vehicles sold in the US, Europe, and China in 2015

USA			EU			China		
(H)EV	Sales	Type	(H)EV	Sales	Type	(H)EV	Sales	Type
Tesla Model S	25,202	IN EV [4]	Mitsubishi Outlander	31,340	PM HEV [5]	BYD Qin	31,898	PM HEV [6]
Nissan LEAF	17,269	PM EV [7]	Renault Zoe	18,469	WR-SM EV [4]	Kandi Panda EV	20,390	PM EV [8]
Chevrolet Volt	15,393	PM HEV [9]	Volkswagen Golf GTE	17,282	PM HEV [9]	BYD Tang	18,375	PM HEV [10]
BMW i3	11,024	PM (H)EV [4]	Nissan Leaf	15,303	PM EV [7]	BAIC E-Series	16,488	PM (H)EV [11]
Ford Fusion Energi	9750	PM HEV [12]	Tesla Model S	15,169	IN EV [4]	Zotye Z100/Cloud	15,467	IM EV [11]
Ford C-Max Energi	7591	PM HEV [12]	Audi A3 e-Tron	11,711	PM HEV [13]	SAIC Roewe 550	10,711	PM HEV [14]
Fiat 500e	6194	PM EV [4]	VW e-Golf	11,124	PM EV [4]	JAC i EV	10,420	PM EV [15]
VW e-Golf	4232	PM EV [4]	BMW i3 Rex	7919	PM HEV [4]	Kandi K10 EV	7665	IM EV [10]
Toyota Prius PHV	4191	PM HEV [9]	Volvo V60 Twin Eng.	6952	PM HEV [9]	Chery eQ	7262	PM EV [11]
Chevrolet Spark EV	2629	PM EV [4]	Kia Soul EV	5800	PM EV [4]	BYD e6	7029	PM EV [16]
Other	12,624		Other	48,242		Other	56,904	
Total US	116,099		Total EU	189,311		Total China	207,382	

Worldwide Sales 550,297. Sales US according to [17], EU [18], China [19]

PM permanent magnet synchronous motor, *IN* induction motor, *WR-SM* wound rotor synchronous motors (without magnets) preferred and the predominant technology applied in (H) EVs [12].

Due to small numbers of end-of-life (H)EVs, dedicated recycling processes have not been implemented at an industrial scale. This is especially true for some components such as batteries, electric motors, and power electronics [24]. Electric motors are mainly made of materials that can be found in combustion engines as well. A slight adaption of the existing recycling routes will supposedly suffice to guarantee a proper recycling for such materials as steel, cast iron, and aluminum. However, the electric motors also contain large quantities of copper and, in the case of PM motors, REE-containing magnets. Especially, the rare earth elements from magnets are lost if they are not fed into dedicated recycling routes [25]. The recycling of REEs from (H)EVs is therefore an important challenge. Moreover, these recycling routes do not yet exist in countries outside China and Japan, even though the recovery of REEs could yield large advantages regarding import dependency, supply criticality, environmental protection, and cost reductions [26, 27].

First, the mine production as well as the subsequent processing of REEs is dominated by China. In 2015, about 85 % of the REEs were mined in China. The further processing of the individual rare earth oxides and metals is carried out to an even higher share in China [28]. Car manufacturers outside China therefore completely rely on imports. Second, the demand for REEs, especially for neodymium and dysprosium, is expected to grow significantly due to the increased use of renewable energies (gearless wind turbines) and (H)EVs (motors). A large share of the produced neodymium and especially dysprosium is already consumed by NdFeB magnets [29]. Third, the increasing demand for neodymium and dysprosium will probably aggravate the balance problem which does not exist in the case of recycling [30]. Fourth, the REE production from ores is associated with a large energy input and radioactive wastes, consumes large quantities of chemicals, and leads to the emission of poisonous gases, especially during digestion and reduction [31]. According to [32], the production of one ton of REOs causes approx. 10,000 m^3 waste gas containing SO_2, HF, and CO_2; and about 75 m^3 of acidic waste water, as well as one ton of radioactive wastes containing thorium and uranium and their decay products. In recycling processes, these environmental problems are eliminated or at least reduced [26, 27].

All these factors mentioned above lead to high and instable prices for REEs in comparison with base metals and to a critical supply situation from the viewpoint of companies outside China. Although prices are comparatively low at the moment, prices peaked around 2011 and are expected to increase again [neodymium: 60.92 US$/kg; dysprosium: 348.13 US$/kg; average prices February 2015—January 2016, metal, min. 99 %, Free-on-Board (FOB) China] [33].

Mainly due to volatile and sometimes high REE prices as well as the supply criticality for companies outside China, many producers and scientists aim at a reduction or elimination of NdFeB magnets in electric vehicles. Apart from the reduction of the costly dysprosium, research and development currently focuses on higher magnet efficiency through design, the development of new magnetic materials, and the optimization of magnet-free motors [4, 31, 34–40]. Nevertheless, against the background of several trends such as vehicle size reduction, lightweight construction, and new drive train concepts, i.e., wheel hub motors [41–43], PM motors will probably continue to assert its predominance in (H)EVs.

Although recycling of NdFeB takes place in China and Japan at an industrial scale (oral communication) and many research publications are available [44], little is known about the essential recycling steps before reuse, reprocessing, or raw material recovery. In the following sections, the complete recycling chain including disassembly of electric motors from end-of-life vehicles, dismantling of the motors, and extraction of magnets as well as recycling options for NdFeB magnets are described and discussed. Many results presented stem from the cooperation project “Recycling of components and strategic metals from electric drive motors—MORE” that was financed by the Federal Ministry of Research and Education of Germany. The participating partners were Siemens AG, Daimler AG, Umicore AG & Co. KG, Vacuumschmelze GmbH & Co. KG, Institute of Applied Ecology, Fraunhofer Institute for Systems and Innovation Research, Friedrich-Alexander-University Erlangen-Nuremberg, and Clausthal University of Technology.

Background

Sintered NdFeB Magnets

Sintered NdFeB magnets are the strongest permanent magnets available today. Their excellent magnetic properties can be traced back to the strongly magnetic matrix phase $Nd_2Fe_{14}B$ featuring high saturation polarization and high magnetic anisotropy. Because of the low Curie temperature and low corrosion resistance of pure $Nd_2Fe_{14}B$, the properties are usually enhanced by alloying other REEs and cobalt. Typically, the alloys contain 60–70 wt% iron, 28–35 wt% REEs (Pr, Nd, Tb, Dy), 1–2 wt% boron, and 0–4 wt% cobalt. The benefit of adding Dy in place of Nd is that it improves coercivity and therefore temperature tolerance. At the highest end of possible operating temperatures (approx. 200 °C), for example, in (hybrid) electric vehicles, NdFeB magnets contain up to 10 wt% Dy. Tb can perform in a similar function but is rarely used due to its high price. Pr can directly substitute Nd to some extent without severe impact on the magnetic properties. Cobalt is commonly added to improve the corrosion resistance. For further improvement of the corrosion resistance, the magnets are phosphated or coated with epoxy resin or metals such as nickel, aluminum, zinc, or tin [45–48]. The magnets are produced via powder metallurgy methods [46, 48]. A typical production route is depicted in Fig. 1.

The most important trends in research and development and production of sintered NdFeB magnets point toward an increase in coercivity using less dysprosium for economic reasons as well as minimization of the related remanence losses. The most promising approaches to achieve this target are a further reduction of the grain size and the grain boundary diffusion process. While the first approach has not been industrially implemented so far, the grain boundary diffusion process was introduced industrially a few years ago [34, 46].

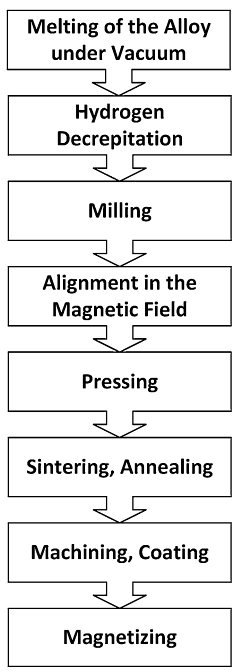

Fig. 1 Production of NdFeB magnets [34]

Permanent Magnet Synchronous Motors

Electric motors use the interaction of electric and magnetic fields to convert electric into mechanical energy. PM motors in EVs typically consist of a cylindrical and magnet-bearing rotor inside a stator. The stator carries field windings that produce a rotating magnetic field when connected to alternating current. Because of the magnets, the rotor must follow the rotating magnetic field thus producing a synchronous movement regarding the frequency of the current [49]. Although there are many factors that influence the effectivity of the motors in general (design, winding styles, materials, reluctance), the applied magnets play a major role in PM motors. Efficiency and power density of the electric motor units depend strongly on the installed magnets. Currently, NdFeB magnets show the best results in PM motors due to their high energy density at reasonable coercivity [50].

PM motors usually consist of cast iron, steel, aluminum, copper, and magnets. If they are combined with a combustion unit (HEVs), other components like plastics and liquids may be applied as well. Table 2 shows typical material compositions for both EV- and HEV-type PM motors. Approx. 3 % of the PM motor weight is contributed by NdFeB magnets in both cases. Nevertheless, according to [31], the impact of the magnets in terms of ecological and monetary costs is disproportionately high.

The magnets are either mounted on the surface of the rotors (surface-mounted permanent magnet—SPM), or buried into the rotor (integrated permanent magnet—IPM). Although SPM rotors are somewhat easier and consequently cheaper to produce, IPM rotors are slightly less prone to exposure [51]. For SPM as well as IPM rotors, a modular design is applied. Figures 2 and 3 exemplarily show a complete rotor, a rotor segment, and dismantled

Table 2 Typical material compositions of permanent magnet synchronous motors [39]

Material	PM-Motor in EVs; 80 kW (kg)	PM-Motor in HEVs; 20 kW (kg)
Steel	34.8	23.1
Aluminum	14.1	4.7
Magnets	2.1	1.4
Cast iron	3.0	0
Copper	8.5	6.4
Polymers	0	0.6
Elastomers	0	0.1
Liquids	0	7.7
In total	62.5	44.0

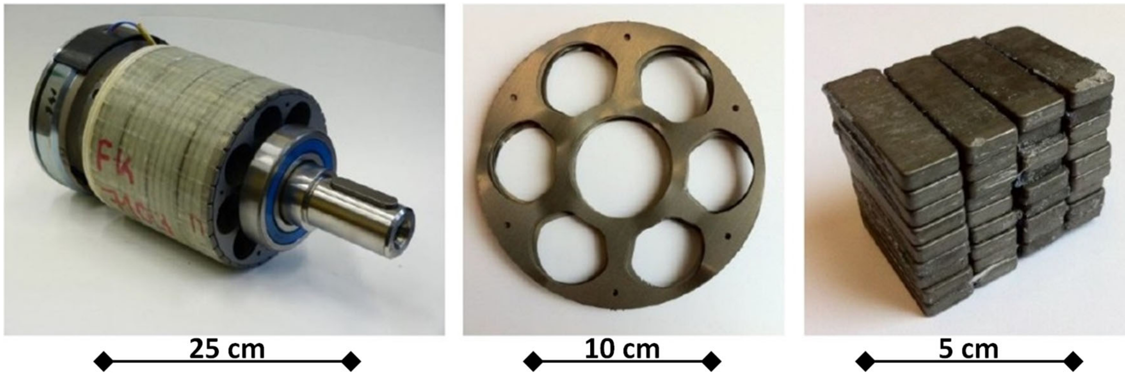

Fig. 2 Rotor, rotor segment, and dismantled magnets (*left* to *right*) of a SPM rotor [52]

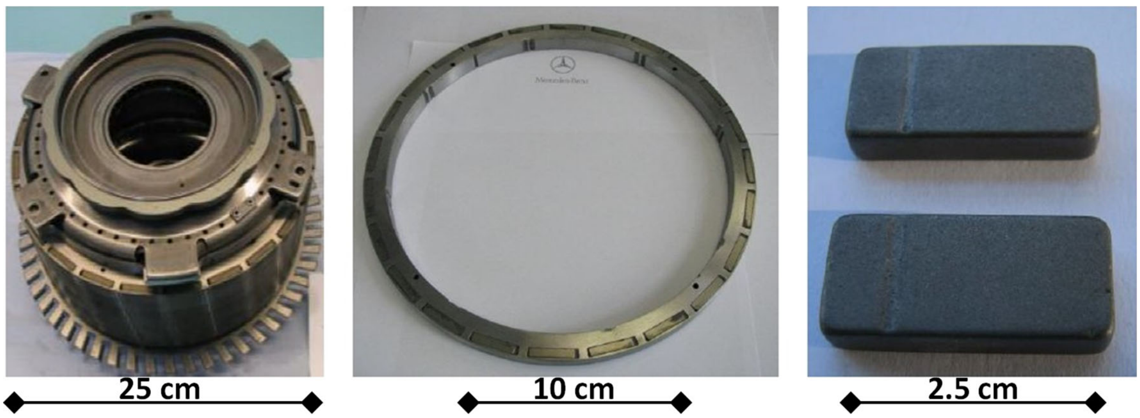

Fig. 3 Rotor, rotor segment, and dismantled magnets (*left* to *right*) of an IPM rotor [52]

magnets for both types. The rotors typically weigh between 10 and 20 kg and contain 1.5–2.5 kg magnets [53].

Recycling of Magnets from PM Motors

In contrast to production wastes, according to [54], there was hardly any recycling of postconsumer REE-containing wastes in 2011 due to missing infrastructure, high process costs, and small material streams. Binnemans et al [44] assumes that recycling rates might have been higher in 2015 due to the intensified research by many market actors. In case of NdFeB magnets, currently approx. 60–70 t/a of production wastes and 60–80 t/a of scraps of different origins are collected in Europe according to own investigations in collaboration with scrap dealers and waste electric and electronic equipment recycling companies. Nevertheless, apart from collection and pretreatment approaches, no recycling process for REE magnets has been established in the western world. The collected wastes are sold to China and Japan for metallurgical recycling. Although, in Europe, the currently collected amount of magnet scrap is very small compared to the annual global magnet production of 127,000 t (2014), increasing returns can be expected in the upcoming decades, especially considering the predicted growth of the (H)EV and renewable energy market [55]. Even though predictions bear great uncertainties, the establishment of a recycling system for magnets from (H)EVs has great potential due to the strong impact of mentioned applications on the overall Nd and Dy demand (see [29]).

The recycling of end-of-life vehicles in Europe mainly consists of the steps depollution, dismantling, shredding, and post-shredding sorting [56]. If REE-bearing motors enter shredding, this leads to lowered and inefficient recovery of some of the contained metals. Especially the cost-intensive REE magnets can hardly be separated by mechanical techniques due to their magnetic properties. They usually report to the iron fraction (magnetic separation) although a considerable share is disseminated over the other fractions, dust, and ferrous equipment parts. The REEs that enter iron or steel recycling are transferred to the slags during smelting due to their ignoble character. An economic recovery is not possible at that point [25].

In order to direct the magnets into a dedicated REE recycling, the motors must be extracted prior to shredding and dismantled down to the rotor/stator level. After dismantling, the SPMs and IPMs have to be removed from the rotor.

Disassembly and Dismantling Down to Rotor/Stator Level

After depollution, combustion engines are usually extracted together with catalysts, tires, and some electronic parts prior to shredding [57]. Apart from components for reuse, this is due to the presence or the concentration of the applied materials and poor recovery during the following processes [56, 58, 59]. This will also be true for electric motors from (H)EVs as the two main value carriers in PM motors—copper from wiring and REEs from permanent magnets—can be recycled more efficiently if the motor is removed from the vehicle and the motors are dismantled. Also, the often massive motors can lead to increased wear of comminution devices. In the case of the automotive industry, only a few studies about the dismantling of (H) EVs or the extraction of specific parts for reuse are available, and they do not cover the entire recycling chain of the REE-bearing magnets [60, 61].

The dismantling of large conventional electric motors and generators by manual labor for remanufacturing or raw material recovery is already state of the art [53]. The resulting main fractions of raw material recovery are currently copper, steel, and, in some cases, aluminum as well as magnesium. Rotor and stator are separated during this process in order to liberate the copper wiring from the stator. The rotor, including the magnets, is fed into the iron fraction.

The MORE project transferred this procedure to end-of-life (H)EVs and tested the disassembly. Figure 4 shows the

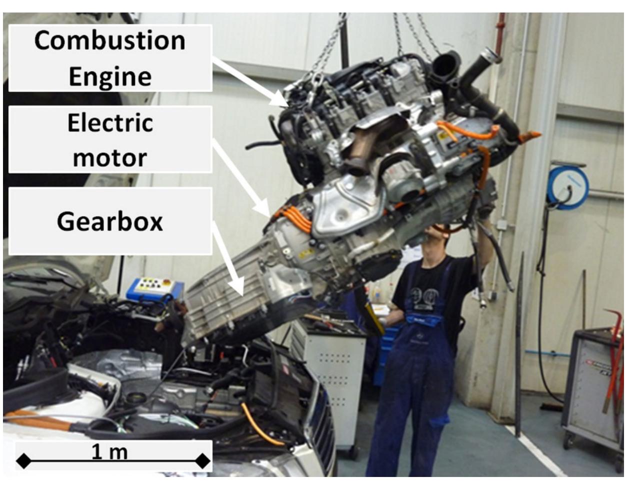

Fig. 4 Extraction of a propulsion system (combustion engine, electric motor, and gearbox) from a series-produced HEV of the manufacturer Daimler AG via a remote-controlled crane [52]

extraction of the propulsion system (combustion engine, electric motor, and gearbox) from a series-produced HEV of the manufacturer Daimler AG via a remote-controlled crane. Disassembly steps and required time were recorded for the disassembly of one HEV type as well as the subsequent dismantling down to the rotor/stator level. 20.5 min was the time required for both the extraction of the propulsion system (see Fig. 4) and the separation of the gearbox. Thereafter, the engine unit was dismantled into combustion engine, and the electric motor and the rotor were extracted in 12 min. It could be demonstrated that the conventional treatment of large electric motors and generators is also feasible for the installed PM motor. The MORE project suggests that the results can be transferred to other (H)EVs in principle. Because the focus of the dismantling lays on the recovery of the copper wiring from the stator, this is true for both IN and PM motors [53]. Nevertheless, disassembly and dismantling might become more difficult, and therefore costly, because of new design concepts, the integration of components, and the trend toward general miniaturization.

Magnet Extraction

As Figs. 2 and 3 show, both SPMs and IPMs cannot be accessed directly either because of bandages or the buried construction. The strong magnetic forces and brittleness of the magnets make their extraction even more challenging. Due to these problems and the low return flow of electric motors, so far, no automated extraction solution is available at an industrial scale.

Within the MORE project, the extraction of the magnets was addressed by the Institute for Factory Automation and Production Systems of the Friedrich-Alexander-University Erlangen-Nuremberg. In the case of IPM rotors, (H)EV motors from long-term testing (about 130.000 km) were used for the experiments. In case of SPM rotors, SPM motors similar to those used in (H)EVs were chosen from other applications due to their limited availability [53].

Different dismantling approaches were followed including manual dismantling, thermal destruction of adhesive bonds including demagnetization, chemical detachment, and tool development. As the labor-intensive manual dismantling is too expensive in high-wage countries, the focus was directed toward the other options which allow automatization at least to a certain extent. While the thermal experiments showed that this approach might lead to hydrogen decrepitation through decomposed organics, erratic and violent detachment of the magnets in case of SPMs, as well as magnet fractures through thermal expansion, the chemical detachment required high amounts of chemicals and energy (see "Reprocessing of the Magnet Alloy" section). Therefore, both approaches were not

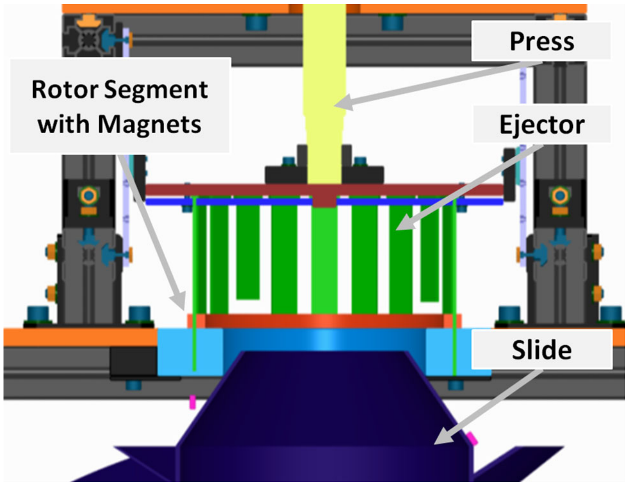

Fig. 5 Concept for the dismantling of IPMs. Adapted with permission from Klier [52]

investigated further, and an emphasis was laid on the development of mechanized and automated dismantling devices [62, 63].

As the designs of IPM and SPM rotors vary greatly, two different concepts for the automated extraction of the magnets were developed. Due to the abovementioned reasons and energy savings, the magnets were not demagnetized prior to extraction. Therefore, all components having direct contact with the magnets had to be manufactured from nonmagnetic materials. The practicability of the concepts was demonstrated with small industrial scale prototypes [53, 62, 63].

For IPMs, rotor-specific ejectors were designed to press out the magnets from their rotor segments. The rotor segments must be separated prior to the treatment. A cylinder with added slides leads the magnets to a conveyor belt with integrated demagnetization via infrared radiation. There are ejector elements and slides of different lengths to allow the magnets to reach the conveyor one by one. This singulation as well as the array of slides is implemented to keep the magnets from attracting each other. Also, the magnets are aligned in order to facilitate further processing steps [62, 63]. The concept for a device for the extraction of IPMs is shown in Fig. 5.

SPM rotors need to be freed of the bandages before magnet extraction. A concept for the removal of the bandage after thermal softening of the glue (below the Curie temperature) and puncturing is shown in Fig. 6. Then, the magnets are shorn off with a nonmagnetic wedge and transported to a storage chamber. The magnets are sorted by polarity and individually stacked with plastic space keepers [62, 63]. The demonstration set-up is depicted in Fig. 7.

In summary, the MORE project demonstrated that an automated magnet extraction is generally possible. However, only a limited number of rotors were processed, and

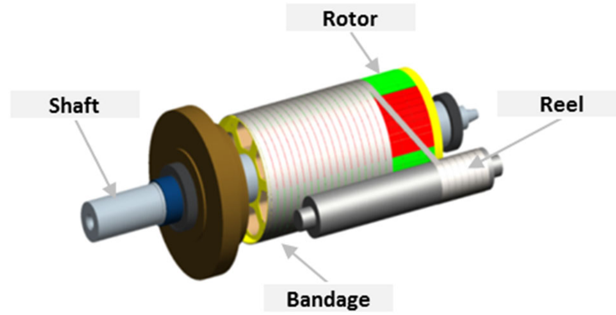

Fig. 6 Removal of the bandages. Adapted with permission from Klier [52]

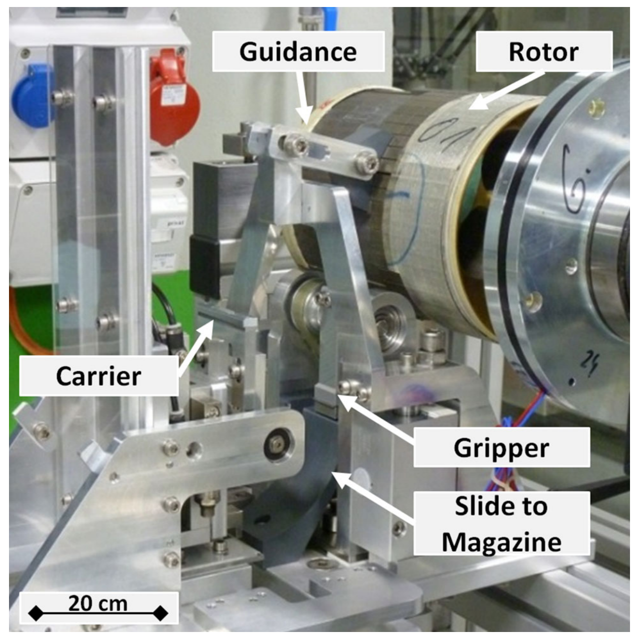

Fig. 7 Demonstration set-up for the dismantling of SPMs. Adapted with permission from Klier [52]

the developed solutions, especially the press for IPMs, need to be made adaptable to varying product designs and dimensions.

Magnet Recycling

In general, recycling processes for NdFeB magnets can be classified into direct reuse, reprocessing of the alloys, and raw material recovery. For a comprehensive review, see [44]. Within the MORE project, all three ways were considered and investigated. In the following sections, the results are presented and critically discussed.

Reuse of Magnets

Theoretically, a direct reuse of the magnets would be economically and environmentally the most favorable way of recycling due to the low energy demand as well as consumption of auxiliary and operating materials [44]. Within the MORE project, different key issues for reuse were addressed including a possible deterioration of the magnetic properties during the life span of the electric motor, disassembly, and dismantling (see "Disassembly and Dismantling Down to Rotor/Stator Level" and "Magnet Extraction" sections) and removal of impurities like glue residues [53].

Regarding the possible deterioration of magnets, the investigations revealed that the magnetic properties are not compromised during operation. This means that, on the one hand, a direct reuse is generally possible but, on the other hand, there will be no demand for magnets as spare parts. A reuse of the magnets in new generations of electric motors was not considered realistic due to progress of development regarding NdFeB magnets as well as electric motors. In addition, the nondestructive disassembly of the brittle magnets poses a difficulty (see "Magnet Extraction" section) as well as the cleaning of the magnets without compromising the dimensions (see "Reprocessing of the Magnet Alloy" section) [53].

Reprocessing of the Magnet Alloy

Prerequisites for a reprocessing of the alloy are magnet scraps of known and homogeneous composition as well as a thorough removal of any impurities such as glue residues and coatings, as the magnetic properties deteriorate even at low impurity concentrations (ppm range). It was defined that the additional C and O contents must not exceed 100 and 300 ppm after cleaning in comparison with the magnet alloy [53].

Because most electric drive motors contain noncoated magnets, the main task in the context of the reprocessing of NdFeB magnets from (H)EVs is the removal of the partly decomposed glue residues. For the removal, chemical as well as mechanical approaches were considered. The investigations revealed that a hydrolysis of the glue is generally possible using caustic soda or dimethylformamide but takes in both cases several hours (>3 h) at elevated temperatures (>120 °C) and requires high amounts of chemicals. Furthermore, some decomposition products cannot be dissolved by hydrolysis [53].

Therefore, a research emphasis was put on a grinding process using disk-finishing machines with SiC-based grinding granulates. With this process, a nearly complete removal of the glue residues fulfilling the set targets was accomplished as long as the magnets possessed no notches or grooves. Only at the grain boundaries, traces of glue and SiC could be detected. Unfortunately, many magnets that are currently applied in electric drive motors contain notches. For this reason, the use of magnets without indentations was included in the design recommendations for future motors [53].

For the actual reprocessing of the magnetic alloy, three possible processes were investigated by the project partner, Vacuumschmelze GmbH & Co. KG, namely the remelting of the alloy in a vacuum induction furnace, purely mechanical comminution, and comminution after hydrogen decrepitation (HD). All these options allow feeding of the cleaned magnet scrap into the established production chain for NdFeB magnets (see Fig. 1).

Although direct remelting is known to be problematic because of the carbon and oxygen contents of the scrap, it was tested in one smelting campaign in a vacuum induction furnace. The oxygen leads to slag formation due to the REEs' strong affinity for oxide slags, and carbon cannot be removed by this process [44]. Also in this smelting campaign, the formation of a porous oxide slag was observed, which entrapped significant amounts of alloy due to poor separation of alloy and slag. This resulted in an overall yield of about 75 %. Furthermore, the stoichiometry of the alloy was out of the specifications after remelting due to the losses of REEs to the slag. Due to these drawbacks, direct remelting was not further investigated [53].

As alternative to remelting, in a next series of experiments, the reprocessings of the magnet powder after comminution without and with HD were investigated. As enough end-of-life magnets from electric motors were not available, the experiments were conducted with production scrap. In the first case, crushers and roller mills were employed for the primary size reduction before jet milling. In the second case, only HD. As the application of the HD process led to a significant better grindability in the jet mills, this process was employed to produce 1000 kg magnet powder containing 300 kg recycling material and 700 kg alloy produced from primary raw materials. The powder was further processed as described in "Sintered NdFeB Magnets" section, and the properties of the magnets were examined [53].

Concerning the magnetic properties, the investigations revealed a remanence loss of 3 % in comparison with magnets produced completely from primary raw materials, whereas the coercivity was not affected. As the remanence decreases linearly with the addition of recycling material, a remanence loss of 1 per 10 % recycling material is to be expected. The remanence loss can be traced back to the formation of nonmagnetic oxides and carbides caused by the additional oxygen and carbon input from the recycling material. This input cannot be avoided even while using completely cleaned magnet scrap because the use of additives in the production process and pressing under incomplete air exclusion lead to trace contents of oxygen and carbon in every magnet. Consequently, a repeated reprocessing of magnets would result in a substantial downcycling over time. As a further parameter, the corrosion resistance was investigated using the highly accelerated stress test in which the magnets were exposed in a nonsaturating autoclave to a humid air atmosphere at 95 % relative humidity, 2.6×10^5 Pa, and 130 °C for 10 days. After the test, the specific weight loss is measured. By means of 30 % recycling material, the specific weight loss increased from <0.1 to 0.8 mg/cm^2 in comparison with magnets produced completely from primary raw materials. This weight loss is still within the producer specification of <1 mg/cm^2, but using higher amounts of recycling material would probably affect the corrosion resistance beyond acceptable limits [53].

From the results described above, it was concluded by the project partners that the reprocessing of the alloy is applicable for NdFeB magnets in general. However, the use of magnets containing the recycling material was not considered realistic within the context of electromobility, as electric motors in (H)EVs require magnets with the highest possible remanence due to the limited space and required lightweight construction. Furthermore, one has to keep in mind that the described experiments were performed with production scrap which contains lower amounts of impurities than the cleaned end-of-life scrap [53].

Raw Material Recovery

As described in the previous section, impurities are a major concern in the recycling of NdFeB magnets due to the related deterioration of the magnetic properties. Hence, the emphasis was laid on raw material recovery enabling the same quality standards as required for primary raw materials by magnet producers. A further requirement was that the recycling process can handle metallic as well as oxidized NdFeB wastes, because oxidized grinding sludge constitutes a major waste stream besides production and end-of-life scrap [53].

For raw material recovery, various approaches and processes have been developed in recent years which can be classified into gas-phase extraction, pyrometallurgical methods, and hydrometallurgical methods. All these processes have various advantages and disadvantages, and so far the vast majority have only been tested in lab-scale trials, at least outside China and Japan. For details see [44]. Due to the aforementioned requirements in the MORE project, a hydrometallurgical approach was found to be most suitable due to its adjustability to various impurities as well as applicability to metallic and oxidized wastes. As depicted in Fig. 8, two processes were developed within the MORE project up to small pilot scale (50 L batches for leaching and precipitation, 7–8 L/h flow rate in solvent extraction), which produce mixed and partly separated REE oxides, respectively. These oxides can subsequently be reduced to the respective REE alloys, either by metallothermic reduction or molten salt electrolysis, and returned to the magnet production [64, 65].

In both processes, the magnets are firstly dissolved in hydrochloric acid. Subsequently, the leach liquor is purified by the precipitation of iron as akaganeite (FeO(Cl, OH)) and cobalt as cobalt sulfide (CoS). The akaganeite can be utilized in the ferrous industry, and the cobalt sulfide in the cobalt industry. In the first process, the REEs, which are praseodymium, neodymium, terbium, and dysprosium, are recovered after purification in one mixed concentrate by oxalate precipitation. After washing and

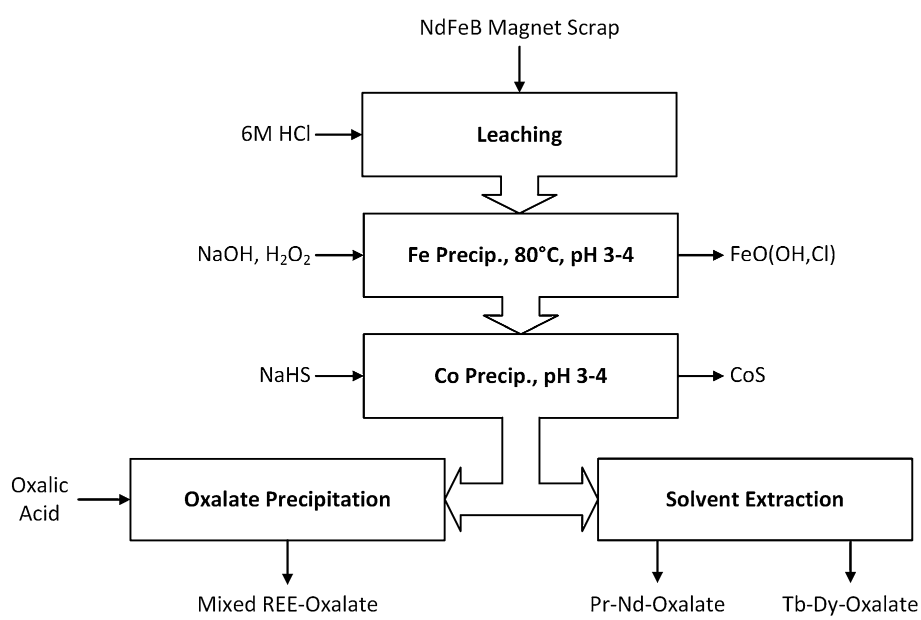

Fig. 8 Simplified flow sheet of the hydrometallurgical recycling processes developed in the MORE project. Adapted from [64]

drying, the oxalates can be converted into the oxides by thermal decomposition. In the second process, the REEs are completely separated by solvent extraction with an organophosphorus extractant (PC-88A) in light and heavy REEs. At the moment, a complete separation at least in light and heavy REEs is necessary for the typically employed reduction and refining methods for Pr, Nd, Tb, and Dy due to their different physical properties such as melting points. Nevertheless, the reduction of a mixed Pr–Nd–Tb–Dy–oxide is thermodynamically possible, but would require the development of an adapted reduction process, which was not part of the MORE project. A detailed description of the process development can be found in [64, 65].

Economic and Ecologic Aspects

The MORE project also calculated the profitability of the entire recycling chain based on the experimental results of the different work packages [53]. The entire recycling chain was surveyed for the financial assessment including the individual profitability of all the recycling sub-processes, i.e., disassembly, dismantling, and raw material recovery. For the latter, only the raw material recovery route including the separation of REEs by solvent extraction was considered, because the other concepts appeared impracticable (see above).

For the calculations, the forecast of the global mobility model [1] for (H)EV market penetration was used. Further assumptions were an average vehicle life span of 15 years, 32.4 % end-of-life vehicle exports to non-European countries, capital and operational expenditure based on expert estimation, a REE recovery rate of 90 %, German labor costs, and REE prices of July 2014. The following scrap prices per kilogram were defined for the other metals and materials: 4 € for copper, 1 € for aluminum, 0.14 € for steel, 2 € for magnesium, and 0.17 € for other end-of-life vehicle materials. Table 2 in section "Permanent Magnet Synchronous Motors" shows the applied generic motor compositions; Table 3 shows the generic composition of the NdFeB magnets. To take possible dysprosium reductions in future magnet generations into account, the calculations were additionally performed with a dysprosium content of 5 % corresponding to a neodymium content of 25 %.

Table 3 Generic composition of the NdFeB magnets for the economic assessment and LCA. Adapted from [50]

Element	Mass percentage
Fe	67
B	1
Co	2
Nd	20
Dy	10

The project concluded that the combination of manual decentralized disassembly and dismantling with a semi-automated centralized magnet extraction and processing would be the most cost-effective solution. The disassembly and dismantling down to the rotor/stator is profitable even without the recovery of the magnets. Revenues are mainly driven by magnesium (combustion engines in HEVs) as well as aluminum in disassembly and copper in dismantling. Regarding the magnet extraction, the transport and extraction costs of the SPM rotors are slightly higher due to the lower magnet content and higher technical difficulties.

The MORE project furthermore assessed the costs and revenues for the hydrometallurgical magnet recycling in a pilot plant with an annual capacity of up to 300 t. A required investment of about 3 million € was calculated including engineering, construction, building, process plant, gas treatment, etc. The depreciation time was set at 10 years. Taking into account the results from the small pilot-scale experiments, approximately 2 € per kg magnets for chemicals and waste (water) treatment were planned. Costs for wages were calculated to be 800.000 € annually for three-shift operation.

For the calculation of potential profits, revenues from produced REE oxides and the costs for magnet processing were compared. Additional costs for transportation and the central magnet extraction were taken into account as well. As Fig. 9 shows, in principle, the magnets can be recycled profitably on the assumed conditions.

In addition to economic assessment, life-cycle assessment (LCA) also was conducted for the developed processes [66]. In this article, only an excerpt of the LCA results for the raw material route including solvent extraction is given. The MORE LCA was conducted according to ISO 14,040/44 based on small pilot-scale data and reviewed by an independent external expert.

Figure 10 shows the system boundaries of the LCA for the recovery of pure neodymium and dysprosium oxide including solvent extraction.

For the different LCAs conducted for the different MORE process routes, the partners agreed upon the generic composition of a typical NdFeB magnet given in Table 3. The functional unit for this LCA is defined as the recovery of 1 kg REE oxide (Nd:Dy ratio = 2:1). It should be highlighted that for the credit calculation for the recovered REEs, a mass allocation as well as an economic allocation was used (see data in Table 4).

Fig. 11 illustrates the LCA results for the impact category global warming potential for the recovery of pure neodymium and dysprosium oxide compared with the primary production route. The necessary additional step from REE oxide to REE metal was taken into account for this calculation.

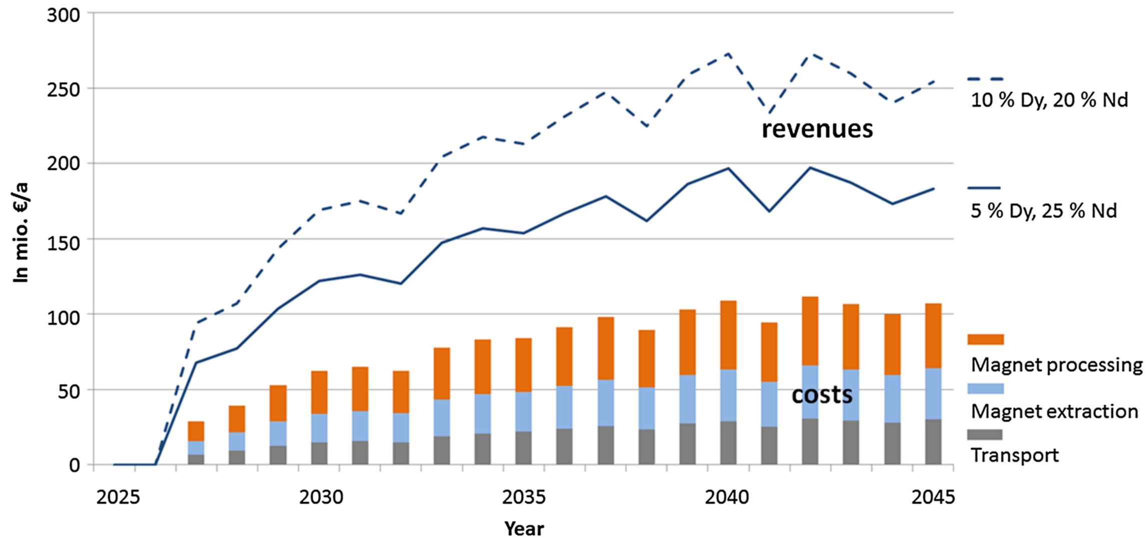

Fig. 9 Costs and revenues for the magnet extraction and processing to neodymium and dysprosium oxides. Adapted from [52]

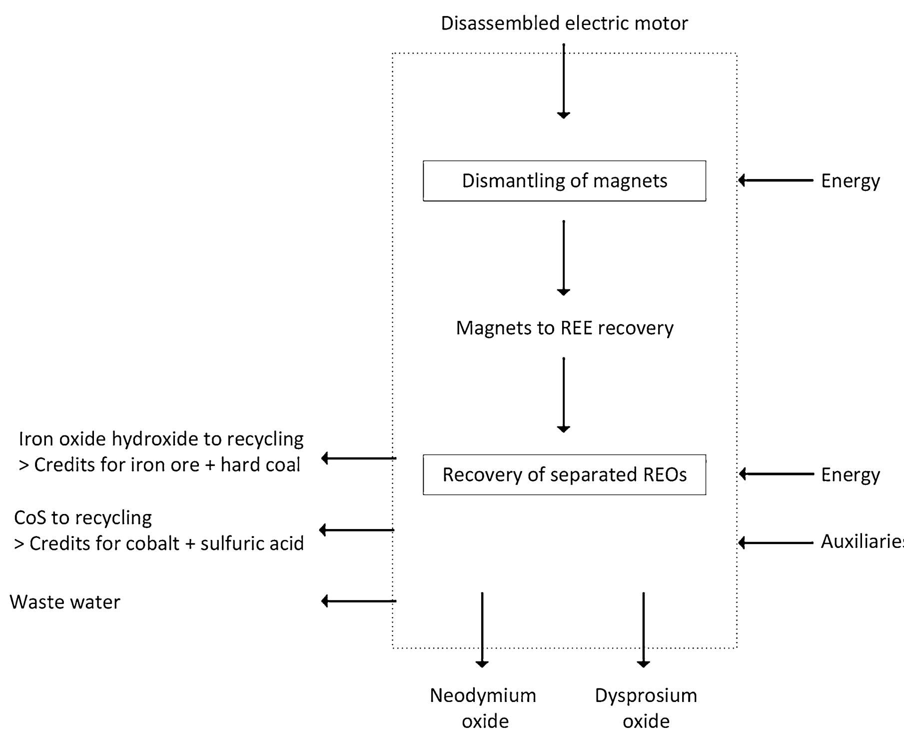

Fig. 10 System boundaries of the MORE LCA (recovery of pure neodymium and dysprosium oxide). Adapted from [66]

Table 4 Comparison of primary Nd and Dy production data for the environmental impact category global warming potential. Adapted from [50]

Allocation approach	Nd	Dy
	(kg CO_2-eq./kg REE)	
Economic allocation[a]	131	1159
Mass allocation	35	35

PE international data for MORE, 2013

[a] REE prices in summer 2013

Also, the results for all other environmental impact categories show net benefits. Therefore, the overall recycling process seems to be very promising from an ecological point of view in comparison with the primary production of REEs. However, the good environmental performance should be verified in future LCA studies if further scale-up takes place, especially considering that the collection of comprehensive LCA data for the primary routes of REEs is a pending and challenging task.

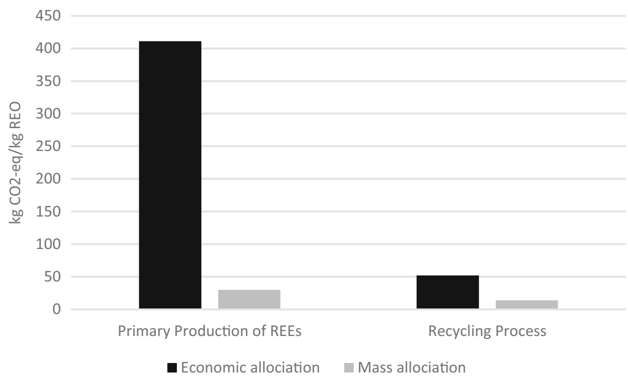

Fig. 11 Global warming potential, recovery of pure neodymium, and dysprosium oxide (solvent extraction route). Adapted from [66]

Summary and Conclusions

In recent years, electromobility in the forms of HEVs and EVs has been strongly promoted by governments and companies leading to a growing market share. In 2015, about half a million (H)EVs were sold globally of which the majority is equipped with PM motors. Although the return numbers of end-of-life vehicles are still low, the recycling practice has to be adapted to the specific components and materials introduced by (H)EVs to enable high recycling rates, especially of minor metals. In case of PM electric motors, the main challenge is the recycling of the contained NdFeB magnets which follow the steel recycling route in the established recycling processes. During smelting, only iron is recovered, whereas the REEs are lost to the slags.

Although the process for an industrial recycling of NdFeB magnets exists at least in China and a few other countries plan to implement similar processes, little information is publicly available about the necessary upstream processes including disassembly of the electric motor from the end-of-life vehicle, dismantling of the motor to rotor/stator level, and magnet extraction. One of the few known activities addressing nearly the entire recycling chain was the German MORE project.

The project demonstrated the technical feasibility of the complete recycling chain. Furthermore, the results indicate that a recycling of the electric motors including the magnets can be profitable even in high-wage countries (metals' prices from 2014) and ecologically advantageous in comparison with the primary raw material production. Prerequisites are cost-effective mechanized and automated disassembly and dismantling techniques, an optimized logistic concept, and sufficient input materials for the processes.

However, as the data were acquired using a limited number of test vehicles and motors, demonstration set-ups, and small pilot-scale plants, a notable uncertainty remains. In addition, the calculations are based on current car models and motorizations and do not figure in trends such as new vehicle designs, wheel hub motors, and integration of power electronics in the electric motor.

Even if the MORE project exemplarily showed that electric drive motors including the NdFeB magnets can be recycled, many challenges and uncertainties remain. Therefore, future research and development is required to improve the databases, to scale up the developed processes and to adapt them to upcoming trends.

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