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Scenario analysis for recovery of rare earth elements from end-of-life vehicles

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Abstract End-of-life vehicles (ELVs) are increasingly being recognized as a possible future resource pool for rare earth elements (REEs). This study provides the amount of REEs that can be recovered from ELVs in Japan based on dismantling survey, chemical identification and substance flow analysis. The REEs were quantified from common passenger vehicles and hybrid electric vehicles. We targeted 17 REEs in estimation of REE contents in ELVs. Four scenarios were developed to explore the recovery of REEs from ELVs. In these scenarios, NiMH batteries and motors containing NdFeB magnets were identified as target components due to they are main REEs carriers; we focused on interpretation of neodymium (Nd) and dysprosium (Dy) owing to they are two of the most critical REEs. The results suggest that 2700 ($\pm$500) tons of REEs can be recovered, of which 520 ($\pm$100) tons and 31 ($\pm$7) tons will be contributed by Nd and Dy in 2030. Meanwhile, the Dy recovered from ELVs can satisfy 23 % ($\pm$6 %) of the demand for NdFeB magnets and NiMH battery cells in automobile production of Japan; the Nd recovered from ELVs can satisfy 49 % ($\pm$9 %) of the production demands.

Keywords End-of-life vehicles (ELVs) · Rare earth elements (REEs) · Scenario analysis · NdFeB magnets · NiMH battery cells

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Introduction

The number of end-of-life vehicles (ELVs) climbed to 40 million worldwide in 2010, of which 12.0 million were contributed by the USA, followed by China and Japan with 3.5 and 3.0 million, respectively [1–3]. As an economic entity, the EU also generated 7.4 million ELVs in 2010 [4]. Consequently, a huge amount of materials related to ELVs, including base metals such as aluminum and iron, and critical metals such as rare earth elements (REEs), are flowing into waste management systems worldwide. The base metals have been recovered from ELVs for years. Currently, one of the hot spots for both academic and industrial fields is to recover critical metals, especially REEs, due to the recent supply risk of raw materials.

The REEs are a group of 17 chemically similar metallic elements: 15 lanthanides, plus scandium (Sc) and yttrium (Y). Because of their unique physical and chemical properties, they are essential for certain vehicle components. For example, misch-metal, which is a mixture of lanthanum (La), cerium (Ce), praseodymium (Pr), and neodymium (Nd), is a substance used for hydrogen storage in nickel metal hydride (NiMH) battery cells [5]. Nd is also a fundamental material used in motor magnets in the form of neodymium-iron-boron alloys (NdFeB magnets) [6]; dysprosium (Dy) is added to magnets to enhance their stability against temperature induced demagnetization [5].

It has been said that for modern industrialized countries, oil is the "blood", steel is the "body", and REEs are the "vitamins" of economy. The European Commission deems REEs as the most critical raw materials group, with the highest supply risk [7]. As also acknowledged by the US Department of Energy (DOE) in their medium-term (2015–2025) criticality matrix, Dy, Nd, terbium (Tb), europium (Eu), and Y are the top-five critical REEs in

relation to their importance for clean energy, and also with respect to risk affecting their supply [8].

Previously, Alonso et al. reported that 0.45 kg of REEs are used in a typical conventional sedan, and that 4.5 kg are present in a full HEV with NiMH battery [9]. Cullbrand and Magnusson estimated that a conventional large car and a hybrid midsize car in the Swedish context contain 27.6 and 531.9 g Nd, and 2.0 and 129.7 g Dy, respectively [10]. In our previous study (hereafter all references to our previous study mean this study), we estimated that the potential for REE recovery from HEV-specific components (NiMH battery cells and hybrid transmission magnets) would reach 2900 t in 2030, and that the recovery potential of Dy would be 45 t in Japan alone [11]. Moreover, Seo and Morimoto indicated that the domestic demand of Dy in Japan in 2030 was estimated to be 1100–1700 t, of which about 500–1000 t was to answer the demand of the automotive industry and 65–95 t to answer the demand for home appliances [12].

For the past two decades, the supply of REEs was in a near-monopolistic condition and related mining practices were environmentally unsustainable. China holds 50 % of the global REE mineral reserves, and accounted for 94 % of the market share in 2011 [13]. However, because of a series of environmental problems such as toxic water and radioactive mud [14], and increased pressure on domestic demand, China lowered its REEs export quota from 50000 tons in 2009 to 31000 tons in 2012 [5], which is a reduction of about 38 %. Therefore, in recent years a great deal of research seeking more sustainable use of REEs appeared worldwide.

In Japan, the "Strategy for Ensuring Stable Supplies of Rare Metals" was established by Ministry of Economy, Trade and Industry (METI) in 2009. From the upstream perspective, this strategy includes development of materials to replace REEs in products, for instance, developing a low Dy content NdFeB magnet [12]. On the other hand, from the downstream perspective, the strategy is to recycle REEs from many end-of-life products, including ELVs. The strategy also emphasized maintaining a stable supply chain and ensuring enough domestic storage.

Many technologies have been developed for the recovery of NiMH batteries and NdFeB magnets, including pyrometallurgical (e.g., electro-slag refining, liquid–metal extraction glass-slag method, and direct melting), hydrometallurgical, and gas-phase extraction methods [15–23]. Additionally, some enterprises such as Hitachi, Ltd.; Honda Motor Co., Ltd.; Japan Metal & Chemicals Co., Ltd.; and Umicore have announced technologies for recovering REE, but the details have not yet been disclosed [5, 24–28]. In 2010, less than 1 % of REEs were actually recycled from end-of-life products [29]. Historically, only small amounts of REEs have been used, and are dispersed throughout many components of a vehicle. However,

increasing amounts of REEs, especially the highly critical elements Dy and Nd, are being used in vehicles (motor NdFeB magnets and NiMH battery cells) [30].

This study focuses on REEs contained in components of conventional passenger vehicles (CPVs) and HEVs. We developed quantified scenarios for exploring the recovery of REEs in the near future (up to 2030), and aimed to provide comprehensive and scientific recommendations for managing ELVs. All 17 REEs were targeted in estimation of REE contents in ELVs. However, we focused on interpretation of neodymium (Nd) and dysprosium (Dy) in recovery scenarios owing to they are two of the most critical REEs.

Materials and methods

Data was obtained from dismantling surveys including chemical analyses conducted during 2012–2015 [31, 32], official statistics, and the literatures. The term "vehicles" in this study included CPVs (small- and standard-sized CPVs) and HEVs. Compact vehicles (engine volume <660 cc displacement), freight vehicles, and plug-in hybrid vehicles, and pure electric vehicles were excluded due to the lack of data. The term "recovery" was defined as the amount of REEs regained from ELVs through certain recovery technologies and processes.

Determining the amount of REEs per ELV

There are three main factors determining the amount of REEs in vehicles: the size of vehicle, the year of production, and the installation rate. Installation rate was considered only for electric power steering and electric air compressor motors. The size of a vehicle determines the different types and weight of the components used, and hence, indirectly affects the REE contents in a vehicle. Therefore, in this study, CPVs were classified into two sizes: small-sized (engine volume ≤2000 cc displacement) and standard-sized (engine volume >2000 cc displacement) CPVs. However, with regard to HEVs, since the statistical data shown that the Toyota Prius is the most common and longest-established HEV in Japan, only the small-sized range was considered [33]. In addition, the contents of REEs in a vehicle can vary according to its production year owing to reasons such as component upgrades. Based on this understanding, it was estimated that CPVs and HEVs underwent three cycles of component upgrades, and thus, fell under the following three categories [32]:

- First period (first-registered before 2003)
- Second period (first-registered in 2003–2008)
- Third period (first-registered after 2008).

The various components containing REEs in vehicles were identified by chemical analysis as listed in Table 1. They were classified into two large groups: common vehicle components and HEV-specific components. The former group was defined as the components commonly equipped in both CPVs and HEVs including motor magnets, printed circuit boards (PCBs), and catalysts. While the latter included the components equipped only in HEVs, for instance, NiMH battery cells and hybrid transmission motor magnets. Li-ion batteries may replace NiMH batteries in the future, but it is difficult to predict the change of battery type so far. Therefore, only NiMH batteries fitted to HEVs were considered in this study.

Electric air compressor motors and electric power steering motors were assumed to be installed in the vehicles from 2nd-period onward, thus the installation rate of them was considered. The term "installation rate" in this study indicates the proportion of first-registered vehicles that are installed with the given components. Based on the statistics, the electric power steering motor was used in the vehicles at a gradual rate. It started from 28 % in the fiscal year (FY) 2003, and rose to 74 % in FY2010 [34–36]. Based on an approximation logarithm, the rate was estimated to increase from 74 % in FY2011 to 91 % by FY2030, as shown in Fig. 1. The historical data related to the installation rate of electric air compressor motor could not be found in the official statistics. However, electric air compressor motors were mostly used in HEVs owing to the
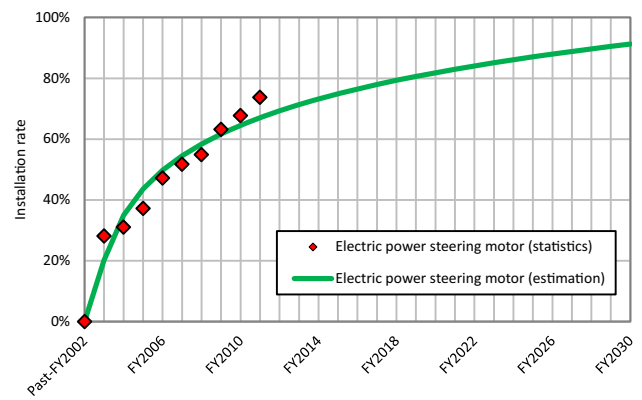

Fig. 1 Installation rate of electric power steering motor. Statistical data was obtained from Sougou Giken Co., Ltd. [34–36]

high electricity cost associated with them; therefore, CPVs were assumed not to equip them.

The concentration of REEs in the sample of electric power steering motor magnet was analyzed using wavelength dispersive X-ray fluorescence spectrometer, while the concentration of REEs in other samples such as other motor magnets, PCB, liquid–crystal display monitor, catalyst, and NiMH battery cells were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) [31, 32]. More details on the concentration of REEs in ELVs have been included in the electronic supplemental materials (ESM1–2). The analyzed samples did not cover small-sized CPVs; their REE contents were estimated from the relative

Table 1 List of equipped vehicle components containing REEs in three periods

Vehicle type:	Small-sized CPV			Standard-sized CPV			HEV		
Time period[a]:	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Common vehicle components									
PCBs of: engine, steering, brake, air big, audio/car navigation, switch in glove box, and harness	●	●	●	●	●	●	●	●	●
PCBs of: speed meter, mirror switch, and door locking receiver	–	●	●	●	●	●	–	●	●
PCBs of electronic toll collection	–	●	●	–	●	●	–	●	●
Electric air compressor motor magnets[b]	–	–	–	–	–	–	–	●	●
Electric power steering motor magnets[c]	–	●	●	–	●	●	–	●	●
Liquid–crystal display monitor	–	●	●	–	●	●	–	●	●
Catalyst	●	●	●	●	●	●	●	●	●
HEV specific components									
PCBs of: Hybrid computer, invertor, and NiMH battery unit	–	–	–	–	–	–	●	●	●
Hybrid transmission motor magnets	–	–	–	–	–	–	●	●	●
NiMH Battery cell	–	–	–	–	–	–	●	●	●

PCBs printed circuit boards

[a] 1st period: pre-2003; 2nd period: 2003–2008; 3rd period: post-2008

[b] Electric air compressor motor magnets were mostly used in HEVs, owing to high associated electricity cost; therefore, CPVs were assumed not to include these components

[c] Electric power-steering motor magnets were assumed to be installed, in part based on the year of first registration [34–36]

weights between small-sized and standard-sized vehicles. For example, dismantled samples were obtained from Toyota Crown vehicles to represent standard CPVs, and from Toyota Prius to represent HEVs; the REE contents of a small-sized CPV were estimated using the weight ratio between small-sized and standard-sized CPVs, which is 70 %. Furthermore, some additional details on HEV-specific components were taken from our previous study [11].

The contents of REEs in various components were calculated by multiplying the concentration of REEs in a specific component by the weight of that component; this information was obtained through a dismantling survey [32]. The contents of REEs per vehicle derived in this study are shown in Table 2.

Forecasting the annual number of ELVs generated

This step is to project the number of ELVs and to estimate the amount of end-of-life common vehicle components.

Firstly, the future size shares for the end-of-life small-sized and standard-sized CPVs were determined in

FY1989–2010, as shown in Fig. 2. From FY1989 onwards, the share of standard-sized CPVs increased until FY2004, reaching its peak (33 %); thereafter, it constantly decreased to FY2010 (29 %) [37]. Owing to the increasing concerns around environmental and energy conservation, we assumed that this current trend of decrease in standard-sized CPVs will last till FY2030. Using linear gradient between 2004 and 2010, the share of standard CPVs was estimated to decrease to 23 % by FY2030.

Secondly, the number of end-of-life CPVs was projected by building a population balance model, which is a dynamic estimation model based on mass balance between input, stock and output of a material or product with a defined lifespan. The proportion of CPVs among the first-registered vehicle was estimated to decrease to 48–58 % (maximum–minimum situations for HEVs) in 2030, from the current 65 %, based on government target for first-registered vehicles issued by METI [38]. The terms "maximum situation" and "minimum situation" derive from the proportion target set for HEVs. The lifespan distribution based on the first year of registration of a

Table 2 Contents of REEs per vehicle in three periods

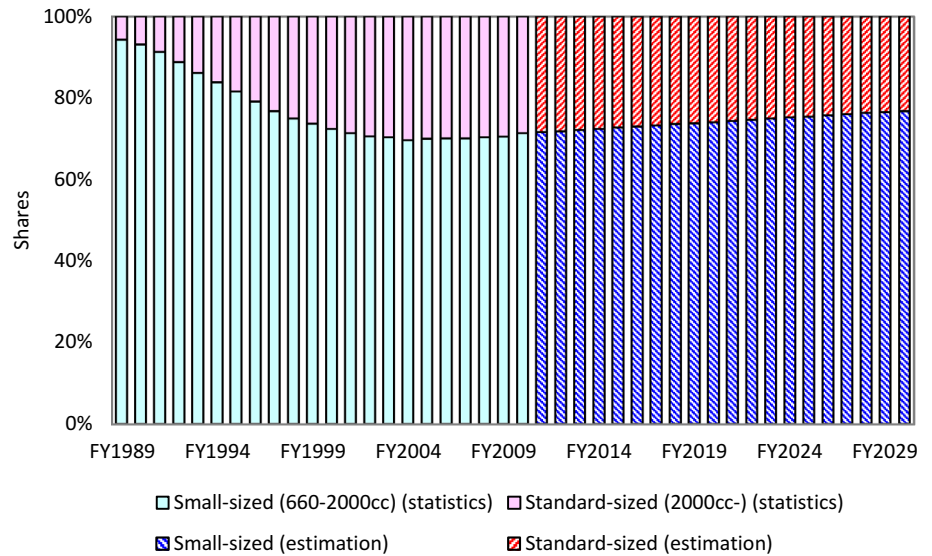| Time period[a]	Small-sized CPV			Standard-sized CPV			HEV		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
(a) Component basis (g per vehicle)									
Components									
Electric power steering motor magnets[b]	–	64.2	64.2	–	94.7	94.7	–	78.8	78.8
Electric air compressor motor magnets[c]	–	–	–	–	–	–	–	18.5	13.3
Other components									
PCBs	0.7	1.8	1.8	3.5	3.6	3.5	0.3	0.9	0.9
Liquid–crystal display monitor	–	0.001	0.001	–	0.002	0.002	–	0.001	0.001
Catalyst	9.2	9.2	9.2	13.6	13.6	13.6	11.3	11.3	11.3
Hybrid transmission motor magnets	–	–	–	–	–	–	486.3	456.9	335.2
NiHM Battery cell	–	–	–	–	–	–	2702.8	2445.4	1801.9
All components	9.9	75.2	75.2	17.1	111.9	111.9	3200.7	3011.8	2241.4
(b) REEs element basis (g per vehicle)									
Elements									
La	1.3	1.4	1.4	2.3	2.3	2.3	870.4	787.8	580.9
Ce	7.9	7.9	7.9	11.7	11.7	11.7	1226.2	1110.3	820.7
Pr	0.04	45.6	45.6	0.2	67.4	67.4	188.6	228.8	135.2
Nd	0.5	19.2	19.2	2.6	28.9	28.9	649.2	660.9	554.6
Dy	0.00	0.9	0.9	0.01	1.3	1.3	148.5	117.5	71.4
Other REEs	0.1	0.2	0.2	0.3	0.3	0.3	117.8	106.6	78.6
Total REEs	9.9	75.2	75.2	17.1	111.9	111.9	3200.7	3011.8	2241.4

PCBs printed circuit boards

[a] 1st period: pre-2003; 2nd period: 2003–2008; 3rd period: post-2008

[b] The installation rate of electric power steering motors was considered

[c] Air compressor motors were assumed to be installed only in HEVs from the 2nd period

Fig. 2 Size shares of end-of-life small-sized and standard-sized CPVs. Statistical data was obtained from AIRIA [37]

□ Small-sized (660-2000cc) (statistics) □ Standard-sized (2000cc-) (statistics)
▧ Small-sized (estimation) ▨ Standard-sized (estimation)

vehicle was considered following the Weibull distribution. The remaining rate function is shown in Eq. (1).

$$F(y,t) = \exp\left\{ -\left(\frac{t+0.5}{\eta} \right)^u \right\} \quad (1)$$

where $F(t)$ is the remaining rate of first-registered CPVs in FY y; y is the first-registered year (=FY1989–2030); t is the vehicle age; u is the shape parameter; η is the scale parameter.

Furthermore, the lifespans of CPVs were assumed to be different depending on the year of first-registered years. The shape parameter u and scale parameter η were estimated by the least squares method according to the statistics on the ownership of vehicles in Japan [3, 36]. Then the annual outputs of end-of-life CPVs from stock during FY2010–2030 were estimated by Eqs. (2, 3).

$$N_{use}(y,t) = N_{1st_{reg.}}(y,0) \times F(y,t) \quad (2)$$

$$N_{EoL\_CPV}(y,t) = N_{use}(y,t) - N_{use}(y,t+1) \quad (3)$$

$$Total_{N_{EoL\_CPV}(Y)} = \sum_{Y=FY1985}^{Y} N_{EoL\_CPV}(y,t=Y-y) \quad (4)$$

where, Y is the counted fiscal year (=FY 2010, 2011,…, 2030); $N_{use}(y,t)$ is the annual number of CPVs in use that are first-registered in FY y of vehicle age t; N1st_reg. is the annual number of CPVs that are first-registered in FY y [=$N_{use}(y,0)$], $N_{EoL\_CPV}(y,t)$ is the annual number of end-of-life CPVs that are first-registered in FY y of vehicle age t; Total_$N_{EoL\_CPV}(Y)$ is the annual total number of end-of-life CPVs in Y.

Thirdly, using the same method as for CPVs, the number of end-of-life HEVs was projected. The estimated remaining curves of CPVs and HEVs are shown in Fig. 3, and the estimated lifespans (when the remaining rate falls
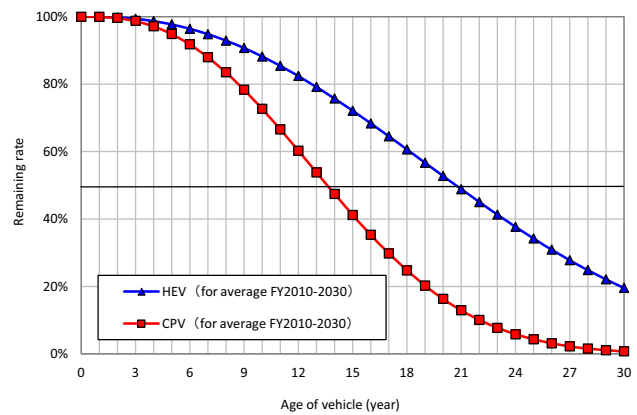

Fig. 3 Estimated remaining curves of CPV and HEV in FY2010–2030

to 50 %) are 13.1 and 20.2 years for CPVs and HEVs, respectively. Our estimation regarding CPVs was basically in accord with the statistical data by Automobile Inspection and Registration Information Association, which reported that the average lifespan of Japanese vehicles is 13.0 years [33]. Additionally, Oguchi and Fuse estimated the average lifespan of Japanese vehicles is 13.0 years [39]. Overall, our findings showed that HEVs have a considerably longer lifespan than CPVs [11].

Estimating REEs contained in the ELVs generated

By multiplying the content of REEs in common vehicle components per CPV and HEV by the number of end-of-life CPVs and HEVs, the annual amount of REEs in end-of-life common vehicle components during 2010–2030 was estimated. Furthermore, by adding the amount of REEs in end-of-life HEV-specific components (result of from our

previous study [11]), the annual amount of REEs contained in ELVs was estimated.

Recovery scenario

Review of recovery technologies

It was reported that the main barriers to recovering REEs are: lack of incentives, inefficient collection, and technological difficulties [5]. Although many laboratory-scale processes have been developed, few have been scaled-up to industrial capacity. A review of REE recovery technologies was conducted to support setting recovery scenarios, as summarized in Table 3.

Mainly, hydrometallurgical and pyrometallurgical technologies were chosen for recovery of ELV components. Hydrometallurgical processes have the disadvantages of consuming large amounts of chemicals and generating large volumes of wastewater. Pyrometallurgical processes consume huge amounts of energy, but such processes can be easily operated [5].

In the case of NiMH battery recovery, the battery cells can be handled via a pyrometallurgical process using waste metallurgical slag (SiO_2 and CaO), where nickel and cobalt are recovered in priority, and REEs are captured within the slag as oxides. It was reported that the slag contains about 71 % of REE content [18], and that more than 99 % of REEs remaining in the slag can be separated at high temperatures (1510–1620 °C) [40]. Subsequently, the remaining REEs oxides can be directly electrolyzed to high-purity REEs (metal phase) through fluorides melts [41]. The combined net recovery efficiency reaches 70 %. On the other hand, NiMH battery cells can also be treated via hydrometallurgical processes. Selective separation of REEs by leaching and precipitation is developed, and about 80–99 % of REEs can be gained in solution depending on their levels of solubility [17, 19, 20]. Overall, REE recovery rates are within the range 70–99 %.

A pyrometallurgical process is available for NdFeB magnets. In this process, 65 % of the REEs in NdFeB magnets are dissolved in molten magnesium (800 °C), then separated by vacuum distillation of the magnesium [42]. Similarly to NiMH batteries, REEs in NdFeB magnets can be recovered by hydrometallurgical process in which roasted magnets are dissolved in sulfuric and hydrochloric acid, thereby leaching 60–99 % of REEs [43, 44]. In this way, REE recovery rates are within the range 60–99 %.

At industrial scales, Hitachi, Ltd. has developed a four-step process applicable to NdFeB magnets from hard disk drive motors, and to air conditioners and other

Table 3 Review of REEs recovery technologies

References	Object	Technology type	Efficiency	Note
Binnemans et al. [5]	NiMH batteries, NdFeB magnets	–	–	A review paper which summarized the status quo of REEs recycling from ELVs including lab-scale and industry-scale process
Tang et al. [18]	NiMH batteries	Pyrometallurgical process	REEs collection rate: 71.4 % (oxide phase)	Lab-scale
Tang et al. [40]	NiMH batteries	Pyrometallurgical process	Separation rate: 99 % (oxide phase)	Lab-scale
Morrice et al. [41]	NiMH batteries	Pyrometallurgical process	–	Lab-scale
Pitrelli et al. [15]	NiMH batteries	Hydrometallurgical process	Recovery rate: about 80 %	Lab-scale
Li et al. [17]	NiMH batteries	Hydrometallurgical process	Over all recovery rate: about 98 %	Lab-scale
Innocenzi and Vegliò [20]	NiMH batteries	Hydrometallurgical process	Dissolution rate: 99 %	Lab-scale
Okamoto [42]	NdFeB magnets	Pyrometallurgical process	Dissolution rate: up to 65 %	Lab-scale
Voßenkaul et al. [44]	NdFeB magnets scrap	Hydrometallurgical process	REEs yield: up to 60 % (86 % purity)	Lab-scale
Koyama et al. [43]	NdFeB magnets	Hydrometallurgical process	Dissolution rate: 80 %	Lab-scale
Honda Motor Co., Ltd. [27]	NiMH batteries	Unknown process	Recovery rate: over 80 %	Industry-scale
Hitachi, Ltd. [45]	NdFeB magnets	A four-step preprocessing process	–	Industry-scale

compressors, but the recovery efficiency remains unknown [45]. Honda Motor Co., Ltd. has developed a process for recovering REEs from NiMH batteries. Although the details of the process have not been revealed, it was reported that REE recovery can exceed 80 % [25].

Overview of scenarios

Accordingly, we developed four scenarios for the recovery of REEs, as shown in Fig. 4. Our target components were NiMH battery and motors containing NdFeB magnets, as they are major carriers for REEs. In this section, collection and recovery rates of existing recovery technologies are considered. However, rather than selecting a representative technology (e.g., pyrometallurgical technology or hydrometallurgical technology) for each scenario, we considered the range of recovery rates between differing technologies for each scenario. To avoid uncertainty regarding future technological advances, we assumed the recovery rates to be constant by 2030. Finally, the amounts of REEs that could be recovered from ELVs during 2010–2030 were estimated.

Scenario 1 (no recovery)

Scenario 1 is the baseline scenario. We assumed that the current situation, in which REE recovery relies solely on spontaneous processes from end-of-life products such as hard disk drives and air conditioner compressors [5], will not change until 2030. The commercial recovery of REEs from ELVs remains limited and unknown. Therefore, scenario 1 assumed that no REEs would be recovered from ELVs by 2030.

Scenario 2 (NiMH battery recovery)

Scenario 2 includes recovery of NiMH battery cells. In Japan, the law for the recycling of end-of-life vehicles requires the recycling of specific components and materials (e.g., airbags and refrigerants) [46]. According to this law, since 2012, secondary batteries were required to be separately collected during the dismantling process and recycled. This can facilitate recovery of the cells from NiMH batteries.

In this scenario, NiMH battery cells are first collected at the dismantling plants. Because the battery is a comparatively independent and valuable component of HEVs, its collection rate was assumed to be 100 %. Subsequently, the NiMH battery cells are subject to recovery processes. The various technologies for handling NiMH batteries offer recovery efficiencies within the range 70–99 %, from which the median value of 84.5 % was used as default value in the scenario.

Scenario 3 (NdFeB magnet recovery)

Scenario 3 points at the recovery of motor NdFeB magnets. Compared with NiMH battery cells, motor NdFeB magnets are difficult to separate from vehicles, because they are usually glued in-place and have strong magnetic fields. Hence, an additional preprocessing step is required. The motors are first preprocessed and then the NdFeB magnets are recovered.

In this scenario, a four-step preprocessing method is applied. Motors are first removed from vehicles and then passed through cutting machines, after which the NdFeB magnets are manually exposed. Secondly, rotors containing NdFeB magnets are disassembled. Thirdly, the NdFeB magnets are demagnetized for safe sorting. Finally, using NdFeB magnet removers, the rotors are subjected to a specific form of vibration at which only the NdFeB magnets re separated and collected [45]. The separation rate was assumed to be 80 % (optimistic). The separated NdFeB magnets are then subject to recovery processes. The available technologies achieve total REE recovery efficiencies of 60–99 %. Similarly to scenario 2, the default recovery rate was set as the median, which is 79.5 %.

Scenario 4 (both recovery)

Scenario 4 integrates scenario 2 and 3, and it was developed to test the gradient and maximum value (both NiMH batteries and NdFeB magnets) of REE recyclability from ELVs.

Sensitivity analysis

A sensitivity analysis was conducted to identify the crucial parameters of our model. In the section of forecast of the generation of ELVs, our estimation mainly relied on government target. Therefore, parameter 1 (number of first-registered vehicles) and 2 (share rate between CPVs and HEVs in first-registered vehicles) were analyzed. In Addition, our model was built upon a population balance model. Thus, the set of parameter 3 (shape parameters) and 4 (scale parameters) were essential. Parameter 5 (content of REEs in common vehicle components) may also lead to deviation, because if contents of REEs per vehicle were assumed to be constant after 2009, the effect of efforts to reduce REEs content according to national strategies such as the strategy for ensuring stable supplies of rare metals will be missed. Parameter 6 (installation rate of electric power steering motor magnets) and 7 (number of NiMH battery cells) were also concerned.

In total, seven parameters were analyzed to understand which parameter inaccuracies can significantly affect our estimation. By increasing one parameter by 10 %, the
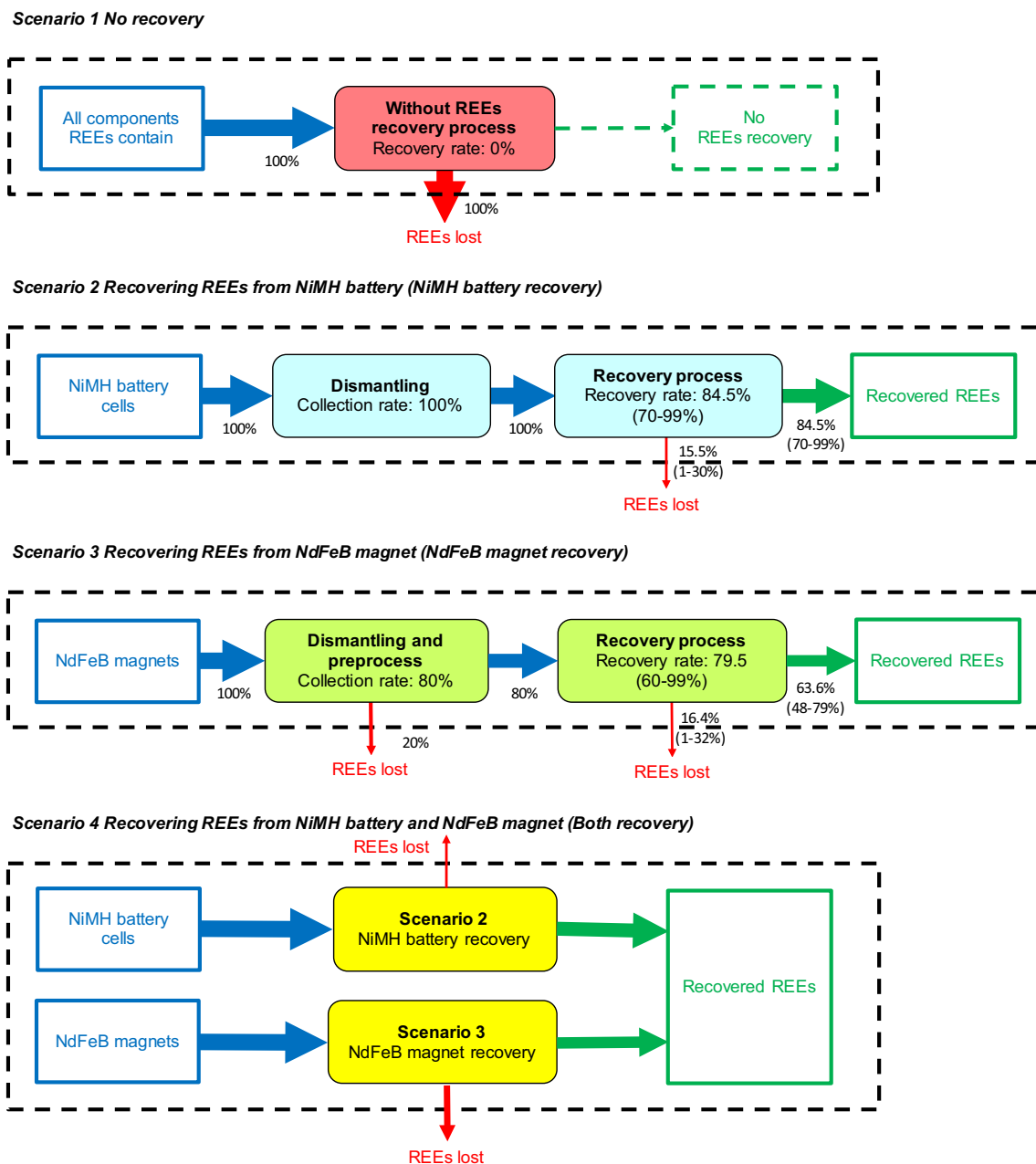
Scenario 1 No recovery

Scenario 2 Recovering REEs from NiMH battery (NiMH battery recovery)

Scenario 3 Recovering REEs from NdFeB magnet (NdFeB magnet recovery)

Scenario 4 Recovering REEs from NiMH battery and NdFeB magnet (Both recovery)

Fig. 4 REEs recovery scenarios. Figures in *bracket* show the range of recovery efficiency

change in results and the default results were compared. This sensitivity analysis involves the sensitivity of not recovered amount, but contents in ELVs. Then sensitivity was defined as according to Eq. (5).

$$S_r(i) = REEs_{r'}(i)/REEs_r(i) \qquad (5)$$

where i is the REE (Nd or Dy), $S_r(i)$ is the sensitivity of element i when parameter r is increased by 10 % ($=r'$), $REEs_{r'}(i)$ and $REEs_r(i)$ are the results, and amounts of element i in ELVs in FY2030 when parameter r and r' are applied.

Result and discussion

Number of ELVs generated during 2010–2030

Because we used the government target for our estimation including minimum and maximum situations, our estimations also had minimum and maximum situations as shown in Fig. 5. The solid curves reflect the situation where the number of HEVs increases the most in 2030. The dotted curves represent a contrasting situation where the number of HEVs follows the minimum increase route.
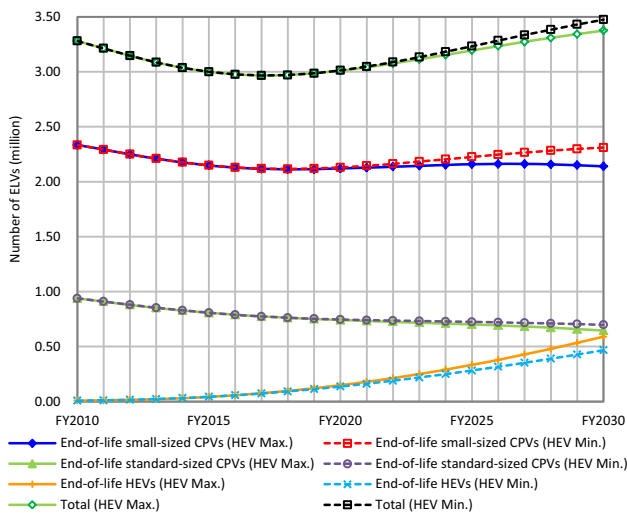
HEV Max.: the maximum situation of HEVs

HEV Min.: the minimum situation of HEVs

Fig. 5 Numbers of end-of-life small-sized and standard-sized CPVs and HEVs. *HEV Max.* the maximum situation of HEVs, *HEV Min.* the minimum situation of HEVs

The result shows that the number of end-of-life small-sized CPVs during 2010–2030 follows a down and up route, and it will decrease to 2.1 million by 2030. The number of end-of-life standard-sized CPVs is constantly in a decreasing route, and it will decrease from 0.9 to 0.6 million during 2010–2030. Regarding end-of-life HEVs, its number will continuously rise till 2030, from 10,000 to a number to that of as standard-sized CPVs, which is 0.5 million.

In general, the number of ELVs during 2010–2030 appears to follow a slight U-shape concave. Approximately 3.3 million ELVs will be generated in 2030, which is nearly equal to the number of ELVs generated in 2010. End-of-life HEVs accounted for only 0.3 % of total number of ELVs generated in 2010, but it will increase to 18 % in 2030. Accordingly, the number of end-of-life HEV-specific components will increase rapidly in these 20 years.

Amount of REEs contained in ELVs during 2010–2030

The result was estimated by adding the amount of REEs in common vehicle components and in HEV-specific components [11] as shown in Fig. 6. Considering the actual case in Japan, which is the one of the largest HEV producing countries in the world, we mainly interpreted the HEV maximum situation, from this section. More details on the HEV minimum situation are provided in the electronic supplemental materials (ESM3–4).

The amount of REEs in ELVs will increase dramatically during 2010–2030, from 130 tons in 2010 to 3400 tons in

2030. NiMH battery cells had the biggest share, and accounts for 87 % of the total amount in 2030. Meanwhile, 12 % of the total is occupied by motor magnets, including 6 % by hybrid transmission motor magnet, approximately 6 % by electric power steering motor magnet, and only 0.3 % by electric air compressor motor magnet. Additionally, 1 % is occupied by other components in 2030. Regarding the type of element, Ce and La had the largest shares because they are the dominant elements in NiMH battery cells, and these battery cells are the main components of REEs in HEV. In 2030, Ce and La occupy 41 and 29 %, respectively, of the total amount of REEs in ELVs. There are 670 and 49 tons of Nd and Dy. More details on the amount of each REE in vehicle components have been included in the electronic supplemental materials (ESM5–6).
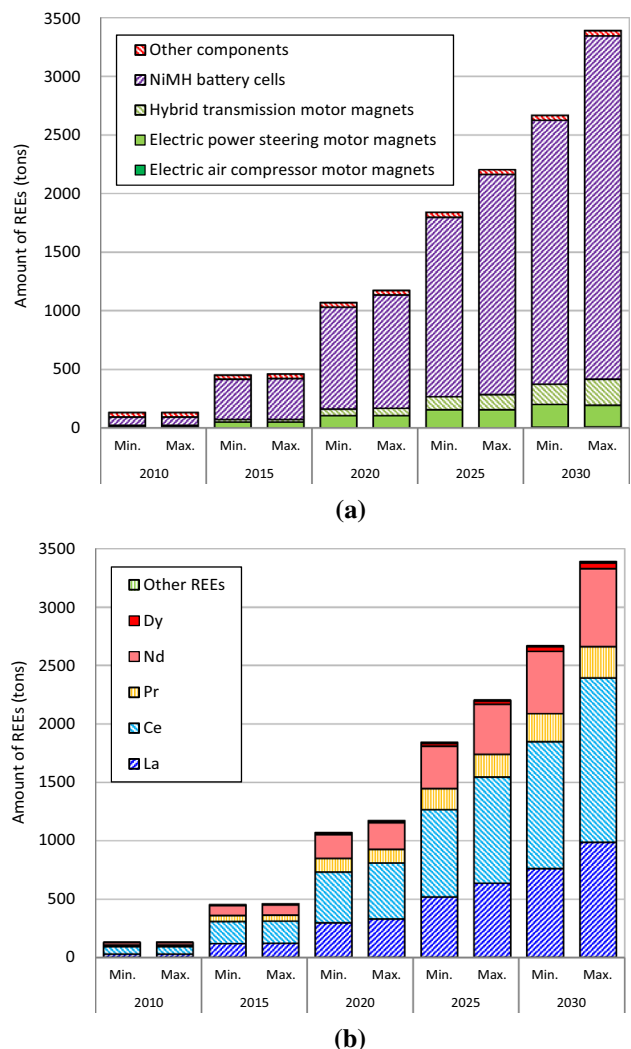

(a)

(b)

Fig. 6 REE contents of ELVs by **a** components and **b** elements (HEV Min. and Max. cases)

Amount of REEs recovered in scenarios

The outcomes of the recovery scenarios in 2030 are shown in Fig. 7. Scenario 1 (no recovery) is the baseline, where no activity of REEs was carried out. Accordingly, the collection and recovery rates are 0 %. In scenario 2 (NiMH battery recovery), the amounts of Ce, La, Pr, and Nd recovered from NiMH battery cells were 1200 ($\pm$200), 830 ($\pm$140), 110 ($\pm$20), and 370 ($\pm$60) tons in 2030, respectively. The absolute amount of other recovered REEs is low, at only 9 ($\pm$1) tons scenario 3 (NdFeB magnet recovery) focuses on recovery of NdFeB magnets. Approximately 85 ($\pm$20) tons of Pr, 150 ($\pm$40) tons of Nd, and 31 ($\pm$7) tons of Dy can be recovered in 2030. According to scenario 4 (both recovery), 2700 ($\pm$500) tons of REEs could be recovered from NiMH battery cells and NdFeB magnets in 2030. The net recovery efficiency in 2030 is about 81 % ($\pm$14 %).

Regarding the recovery of REEs, Nd and Dy are essential from the viewpoint of criticality and practice [5, 8]. Furthermore, their recovery is potentially profitable: Dent reported average Ce and La prices of 9 USD/kg, whereas those of Nd and Dy once were more than 450 and 3400 USD/kg, respectively as of 2011 [47, 48]. Although the prices were dropped recently, they are still very valuable.

A comparison between components in scenario 4 in 2030 is shown in Fig. 8. For both of recovering Nd and Dy, hybrid transmission motors magnets contribute the most which account 21 and 91 % of the total amount. Referring other motor magnets, electric power steering motor magnets and electric air compressor motor magnets account for 7 % ($\pm$0.4 %) of the total Nd recovery, and the Nd recovered from the former is about seven times larger than the latter. On the other hand, these two motor magnets share 8 % ($<\pm$0.1 %) of total Dy recovery, and the Dy recovered from electric power steering motor magnets is almost two times of it recovered from electric air compressor motor magnets. Moreover, considering that the installation rate of electric power steering (and hence motor magnets) in vehicles increased from 44 % in 2005 to 67 % in 2010, the amount of Nd and Dy recovered from that component would increase over time. Therefore, collection of these magnets from both end-of-life CPVs and HEVs is likely to contribute to the recovery of Nd and Dy. The recovery priority in motor magnets should be sequentially given to hybrid motor magnets, electric power steering motor magnets and electric air compressor motor magnets in the perspective of quantity.

Using the number of first-registered vehicles and content of REEs per vehicle, the demands for Nd and Dy for vehicles in Japan could be also estimated through our model. Improvements in NiMH battery technology result in less use of Nd in batteries, but our dismantling survey indicated that there was no substantial reduction in the use of Nd for NdFeB magnets [31, 32]. We estimated that 470 tons of Nd will be required to produce NiMH battery cells, and 590 tons of Nd and 130 tons of Dy will be required for NdFeB magnets in motors in 2030. The recovered Nd from ELVs can satisfy 49 % ($\pm$9 %) of the demands for production of NdFeB magnets and NiMH battery cells. In addition, 23 % ($\pm$6 %) of Dy demand for

Fig. 7 REEs recovered from ELVs under each scenario in 2030 (HEV Max. case). Ranges reflect the recovered REEs by different recovery efficiencies
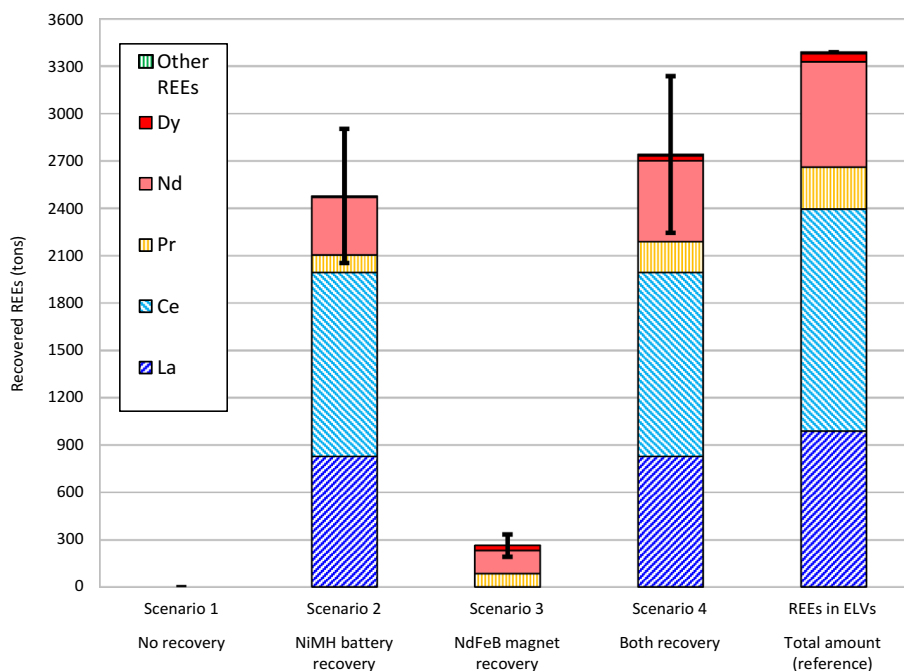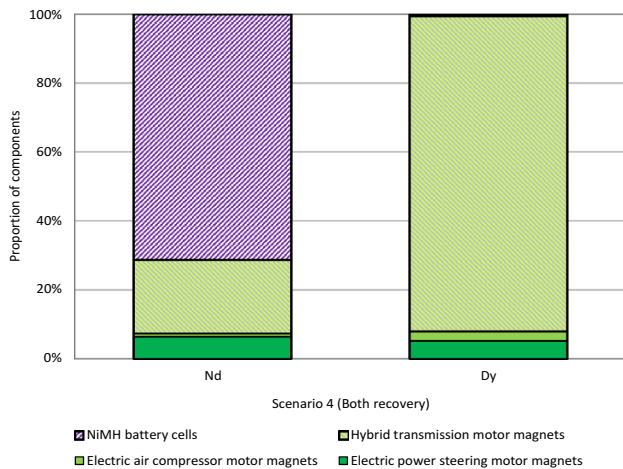
Fig. 8 Comparison of components with respect to Nd and Dy recovered under scenario 4 in 2030 (HEV Max. case)

automobiles (motor magnets) can be satisfied by the recovery from ELVs. Further details on demand and recovery in 2010 and 2020 have been included in the electronic supplemental materials (ESM7–8).

Sensitivity and uncertainty

As shown in Table 4, the most sensitive parameter for the Nd content of ELVs is parameter 3 (shape parameters of remaining rate function): A 10 % increase in this parameter results in approximately −8 % of Nd change in ELVs. In addition, parameter 1 (number of first-registered vehicles), 2 (shares of CPVs and HEVs as first-registered vehicles), and 7 (amount of NiMH battery cells) are also sensitive, and can account for 7, 6, and 6 % of changes, respectively. The most sensitive parameters for Dy content in ELVs are parameter 4 (scale parameters of remaining rate function) and 5 (content of REEs in common vehicle components), which account for −11 and 10 % changes in Dy content, respectively. Parameter 1 is also sensitive, accounting for

5 % change. In summary, our estimation model is comparatively sensitive to changes in parameter 3, 4, and 5.

In our estimation model where recovery efficiency was set to be constant during 2010–2030 and reuse of components was not concerned. They are remaining uncertainties. Moreover, parameter 5 may cause large uncertainties because the content of REEs per vehicle has a wider range between previous studies as shown in Table 5.

There is a considerable difference between the studies by Alonso et al. [9] and Widmer et al. [49]. For example, Nd and Dy contents in the former are 135 and 915 times larger than that in the latter. Compared to their studies, the content of REEs in our study and the study by Cullbrand and Magnusson [10] are in a middle range.

Three reasons can be identified for this wide difference:

- The first is that manufacturers differ from each other, and therefore the components differ. For example, the estimation by Alonso et al. [9] was based on mixed brands (Ford and Toyota), and our estimation was focused on Toyota.
- The second is that the scales of samples also differ from each other; for example, Widmer et al. [49] only examined electronic components (i.e. the catalyst containing Ce and La, is excluded), whereas the present study focuses on NdFeB magnets and NiMH batteries. Furthermore, the future possible use of Li-ion batteries was excluded from the present study due to lack of data.
- The third is that the calculation methods and considered components are different. For instance, Cullbrand and Magnusson [10] analyzed using information from suppliers, and we estimated through dismantling survey, chemical analysis, and statistics.

The differences of content of REEs in different studies can be larger than ten times. The result in Table 3 shows that when the content of REEs is increased by 10 %, it results in approximately 5 and 10 % changes of the Nd and

Table 4 Results of sensitivity analysis

Parameter		$S_r(Nd)$ Sensitivity to Nd content in ELVs in 2030	$S_r(Dy)$ Sensitivity to Dy content in ELVs in 2030
1	Number of first-registered vehicles	1.07	1.05
2	Share rate between CPVs and HEVs in first-registered vehicles	1.06	1.04
3	Shape parameters of remaining rate function	−1.08	−1.03
4	Scale parameters of remaining rate function	−1.05	−1.11
5	Content of REEs in common vehicle components	1.05	1.10
6	Installation rate of electric power steering motor magnets	1.02	1.03
7	Amount of NiMH battery cells	1.06	1.00

$S_r(i)$ is the sensitivity of element i (=Nd, Dy) when parameter r is increased by 10 % compared with the default value

Table 5 Comparison of REE contents per vehicle

REEs per vehicle (g per vehicle)		Widmer et al. [43][a]	Cullbrand and Magnusson [9] (conventional large and hybrid midsize)[b]	Alonso et al. [8][b]	This study[c]		
					1st	2nd	3rd[c]
CPV	La	12.0	0	8.1	2.3	2.3	2.3
	Ce	0.02	12.9	81.0	11.7	11.7	11.7
	Pr	0.07	2.5	30.6	0.2	67.4	67.4
	Nd	2.2	27.6	297.0	2.6	28.9	28.9
	Dy	0.03	2.0	27.5	0.01	1.3	1.3
	Others	0.08	0.7	5.8	0.3	0.3	0.3
	Total	14.4	45.7	450.0	17.1	111.9	111.9
HEV	La	–	6.7	–	870.4	787.8	580.9
	Ce	–	0.31	–	1226.2	1110.3	820.7
	Pr	–	4.0	–	188.6	228.8	135.2
	Nd	–	531.9	–	649.2	660.9	554.6
	Dy	–	129.7	–	148.5	117.49	71.4
	Others	–	21.49	–	117.8	106.6	78.6
	Total	–	694.4	4500.0	3200.7	3011.8	2241.4

1st period: pre-2003; 2nd period: 2003–2008; 3rd period: post-2008

[a] Samples were from 2003 to 2008

[b] There is no sample due to direct use of data from slippers

[c] Samples were from Toyota Crown and Prius produced in 1997 and 1999

Dy contents in ELVs. Accordingly, if the content of REEs shows a deviation by ten times, the estimation will have five and ten times the deviation of Nd and Dy contents. This implied that the efforts of reducing REEs content would greatly influence the amount of REEs recovered in the future.

Conclusions

This study conducted a scenario analysis aimed to clarify the REEs in ELVs in Japan in the near future, and then explored the recovery of REEs through scenarios. The obtained conclusions were shown below:

- The total amounts of REEs in ELVs will increase from 130 to 3400 tons during 2010–2030. In total, 2700 (±500) tons can be recovered from NiMH battery cells and motor NdFeB magnets in 2030, of which 520 (±100) and 31 (±7) tons will be contributed by Nd and Dy, respectively. The net recovery efficiency in 2030 is approximately 81 % (±14 %).
- Comparing common vehicle components and HEV-specific components, the former accounts about 7 % (±0.4 %) of the total recovery of Nd, and about 8 % (<±0.1 %) of the total Dy; electric power steering motor is the dominant component in comparing common vehicle components.

- Dy recovered from ELVs can satisfy 23 % (±6 %) of the demand for automobile production of Japan in 2030; meanwhile, Nd from ELVs can satisfy 49 % (±9 %) of the production demands for motor NdFeB magnets and NiMH battery cells.

It is beneficial to recover magnets from electric power steering and electric air compressors units, together with those from hybrid transmission motors. In addition, by fully activating the incentive in our scenarios, net recovery rate has a wide range of 67–94 %. However, the technologies required to achieve such high recovery rates are mainly limited to laboratory-scale at present. Thus, further progress is required to improve the viability of REE recovery processes. The recovery potential of 3400 tons REEs from ELVs by 2030, estimated in the study, provides support for policies to expand facilities for: (a) the dismantling of HEVs, (b) the recovery of REEs from motor NdFeB magnets and NiMH batteries cells.

The use of different vehicles and methodologies results in widely various estimation of the REE contents of vehicle components. Hence, REE recovery schemes should consider the types of automobiles and other factors relevant to local circumstances.

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