Evaluation of the Recycling Potential of Rare Metals in the Passenger Vehicle Sector in Japan

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Abstract: Japan and many other countries worldwide are moving toward carbon neutrality. Hence, CO_2 reduction has become an important issue for the transportation sector. Clean energy vehicles (CEVs), which emit less CO_2, are being introduced, but CEVs consume more rare metals such as lithium, cobalt, and nickel than do gasoline vehicles, owing to their batteries and other components. Moreover, rare metals face risks regarding the supply of primary resources. Therefore, forecasting and analyzing the supply of secondary resources from rare metal recycling is necessary for the introduction of CEVs in Japan. In this study, the number of scrapped passenger vehicles was estimated using the Weibull distribution, and the amount of recyclable rare metals was evaluated. The results show that the amount of recyclable rare metals is expected to increase significantly by approximately 2,600 tons in 2030 compared with 2021 as the number of scrapped CEVs increases in the improvement of the recycling rate scenario. However, demand will also increase significantly; therefore, arterial and venous automotive industries must further collaborate to increase the amount of recycling and maximize its utilization.

Key words: Automotive industry, circular economy, rare metal, recycling.

1. Introduction

Japan and many other countries worldwide are moving toward carbon neutrality. To reduce CO_2 emissions from the transportation sector, the introduction of clean energy vehicles (CEVs), such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs), is being promoted.

Thus, previous studies on CEVs have mainly focused on CO_2 emissions and fuel consumption, such as Nonaka and Nakano [1], Kananari *et al.* [2], and Fulton *et al.* [3]. However, these studies did not consider the sustainability of metal resources, such as rare metal elements. For example, the lithium-ion batteries used in BEVs require large amounts of rare metals, and demand is expected to increase as CEVs become more widespread. Additionally, the primary resource supplies of rare metal elements are considered insecure owing to their low reserves-to-production ratios and the uneven distribution of their reserves among different regions. Therefore, evaluating the sustainability of rare metals by forecasting and analyzing the supply of secondary resources from recycling is critically important.

A previous study on the supply of metal resources in the automotive industry by Karai *et al.* [4] focused on copper recycling for automobiles, home appliances (refrigerators, air conditioners, washing machines, and televisions), and housing, and estimated and analyzed copper supply. However, they assumed that CEVs were uniformly twice as large as gasoline vehicles (GVs) regarding the amount of copper used per passenger vehicle, and did not consider differences among HEVs, PHEVs, BEVs, and FCVs. The demand for and supply of metals and the resulting price fluctuations are likely to change the technological strategies of companies and government policies related to CEVs. Thus, differences among CEVs must be considered. Additionally, to estimate the number of retired passenger vehicles, Karai *et al.* [4] estimated the parameters of the probability distribution based on the number of passenger vehicles sold and owned from 1985 to 2006. However, the average age of passenger vehicles increased from 4.6 years in 1985 to 6.9 years in 2006 and 8.7 years in 2020. [5] Therefore, the work of Karai *et al.* [4] does not reflect the recent increase in the service life of passenger vehicles.

Yano *et al.* [6] estimated the number of end-of-life vehicles (ELVs) among passenger HEVs in Japan and the amount of recyclable rare earth elements. However, both Yano *et al.* [6] and Karai *et al.* [4] did not consider the recycling potential for rare metal elements.

Li and Fujikawa [7] and Li *et al.* [8] estimated ELVs in China and the amount of recyclable iron, plastic, and nonferrous metals. Both studies used China as their target region. They also did not distinguish between types of CEVs.

In response to these issues, this study targeted rare metal elements, such as lithium, cobalt, and nickel, in Japan. Furthermore, this study considered the lengthening of vehicle life spans in the estimates of number of ELVs and examined the differences in the amount of rare metals used per vehicle among CEVs when evaluating the amount of these metals that could be recycled. The purpose of this study is to inform corporate CEV development plans and governmental CEV diffusion policies through these evaluations and analyses.

Section 2 provides an overview of the research methodology. Section 3 presents and discusses the results of the calculations made using the research methods described in Section 2. Section 4 provides a summary of this study and future issues.

2. Research Methods

2.1. Model for predicting the number of ELVs

A model that predicts the number of ELVs was a pre-requisite for the calculations regarding the recycling of rare metals.

An automobile is composed of many parts, and a malfunction of the weakest part leads to malfunction of the entire automobile. In other words, the malfunction of the entire automobile is determined not by the average failure characteristics of all components, but by the failure characteristics of the weakest part. The time distribution of the malfunction rate of a product with these characteristics is known to follow the Weibull distribution. [9]

Therefore, in this study, the Weibull distribution was used to estimate the number of ELVs. The cumulative retirement and survival probabilities based on the Weibull distribution are expressed as shown in Eqs. (1) and (2), respectively.

$$W(k) = 1 - \exp\left[-\left(\frac{k}{\eta}\right)^m\right] \tag{1}$$

$$RP(k) = 1 - W(k) = \exp\left[-\left(\frac{k}{\eta}\right)^m\right] \tag{2}$$

where:

k: Vehicle age

m: Shape parameter (*m*>0)

η: Scale parameter (*η*>0)

W(k): Cumulative retirement probability of a vehicle of *k* years of age [%]

RP(k): Survival probability of a vehicle of *k* years of age [%]

The shape parameter *m* and the scale parameter *η* were estimated to minimize the sum of the squares of the errors between the estimated survival probability and the actual survival rate in FY2020, which was obtained from the number of units sold in each registration year and the number of remaining units in FY2020 [5]. The number of remaining units represents the number of units sold in each registration year that have not been retired by FY2020. As a result, the shape parameter *m* and the scale parameter *η* were estimated to be 2.59 and 14.44, respectively.

Based on the cumulative retirement probability from Eq. (1), the probability of retirement and the number of retired vehicles in a single year at a certain point in time can be expressed via Eqs. (3) and (4), respectively.

$$WS(t,k) = W(t,k) - W(t-1,k) \tag{3}$$

$$S_i(t) = \sum_{k=1}^{n} P_i(t,k) WS(t,k) \tag{4}$$

where:

t: Time [Year]

i: Vehicle type [GV, HEV, PHEV, BEV, FCV]

WS(t, k): Retirement probability of a vehicle of *k* years of age during year *t* [%]

W(t, k): Cumulative retirement probability of a vehicle of *k* years of age during year *t* [%]

$S_i(t)$: Number of retired vehicles of vehicle type *i* during year *t* [units]

$P_i(t, k)$: Number of vehicles sold of vehicle type *i* during year *t-k* [units]

2.2. Prediction model for the recyclable amount of rare metals

The amount of recyclable rare metals can be expressed as shown in Eq. (5), based on the probability distribution of the number of retired vehicles in the previous section.

In this study, the recycling rate in the future was set based on the European Union's proposed battery regulation [10], but this may change depending on future technological developments.

$$MR_j(t) = \sum_{t} S_i(t) C_{ij} B(t) R_j(t) \tag{5}$$

where:

$MR_j(t)$: Amount of recyclable rare metal *j* in year *t* [g]

C_{ij}: Amount of rare metal *j* used (contained) in a vehicle of type *i* [g/unit]

B(t): Recovery rate of ELVs in year *t* [%]

$R_j(t)$: Recycling rate of rare metal *j* in year *t* [%]

3. Simulation Results

3.1. Scenarios for rare metal recycling

The demand for rare metals is expected to increase in the future due to the popularization of CEVs and the batteries used in these vehicles. In addition, the primary supply of rare metals is considered unstable because their reserves are unevenly distributed in different regions.

Therefore, the supply-demand balance of rare metals is expected to become tight, and recycling of rare metals has become an important issue.

Therefore, in this study, two scenarios were set for the recycling rate of rare metals contained in ELVs: (1) improvement of the recycling rate scenario and (2) maintaining the current recycling rate scenario (Table 1).

The current recycling rate was set based on previous studies [11].

The following section presents the simulation results for each scenario and their comparison.

Table 1. Recycling rate of rare metals in 2030

Scenario	Lithium	Cobalt	Nickel
Improvement of recycling rate	70.0%	95.0%	95.0%
Maintain current recycling rate	0.5%	32.0%	60.0%

3.2. Estimation of the number of ELVs

Based on the results of the calculation of the number of ELVs (Fig. 1 and Fig. 2), the total number of ELVs was expected to gradually decrease from approximately 4.3 million in 2021 to 4.1 million in 2030. Moreover, although GVs accounted for a high percentage of the total, the number of scrapped CEVs was predicted to gradually increase owing to a decrease in GV sales and an increase in CEV sales. In particular, the number of HEVs scrapped will likely increase from approximately 400,000 in 2021 to approximately 1.1 million in 2030, as shown in Fig. 2. Fig. 2 shows a breakdown of the number of ELVs in CEVs shown in Fig. 1.

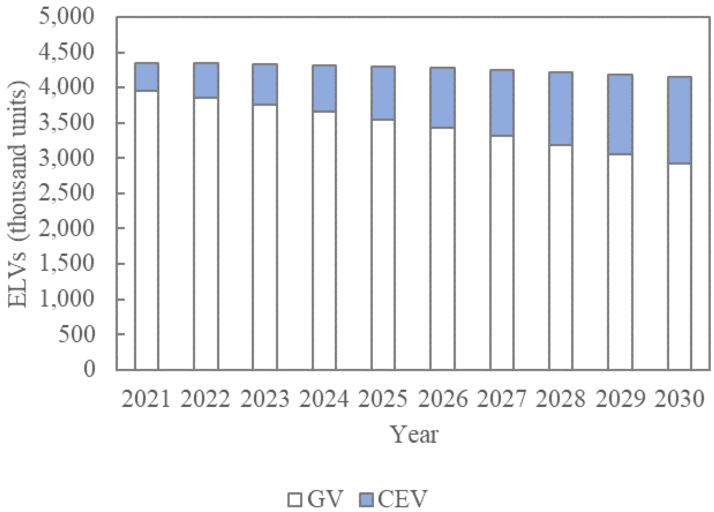

Fig. 1. Number of ELVs (GV and CEV) [thousand units].

Fig. 2. Number of ELVs (HEV, PHEV, BEV, and FCV) [thousand units].

3.3. Estimation of the amount of recyclable rare metals

As shown in Fig. 3-5, in the improvement of the recycling rate scenario, the recyclable amount of lithium, cobalt, and nickel was expected to increase significantly from approximately 4, 45, and 170 tons in 2021 to around 330, 720, and 1,800 tons in 2030, respectively. In particular, as the number of scrapped BEVs, which contain many rare metals, increases, the amount of recyclable metals has increased significantly.

On the other hand, in the maintain current recycling rate scenario, the amount of lithium, cobalt, and nickel that could be recycled in 2030 was projected to be approximately 2, 240, and 1,100 tons, respectively. Since the recycling rate is maintained at the current level, this result is attributed to the increase in the number of CEVs scrapped. However, compared with the improvement of the recycling rate scenario, the recyclable volume has decreased significantly, indicating the importance of improving the recycling rate. In particular, the current recycling rate of lithium is low, which could become a bottleneck for BEV production.

In the improvement of the recycling rate scenario, the total amount of rare metals that can be recycled was projected to increase from approximately 220 tons in 2021 to 2,900 tons in 2030, as shown in Fig. 3-5. Given that the total amount of rare metals recycled by all industries in 2019 was approximately 300 tons [12] of cobalt and 4.5 tons [12] of nickel, for a total of approximately 305 tons, this would be a significant increase. Although the predicted total number of scrapped vehicles gradually decreased, the predicted amount of recyclable rare metals should increase because of the increased number of scrapped CEVs, which contain more rare metals than GVs. These recycling amounts are equivalent to the possible production of approximately 60,000 additional EVs in 2030. Nevertheless, considering the sales volume in Japan, further expansion of the recycling volume is required. To increase the amount of recycled materials and maximize their utilization, further cooperation between the arterial and venous automobile industries will be necessary.

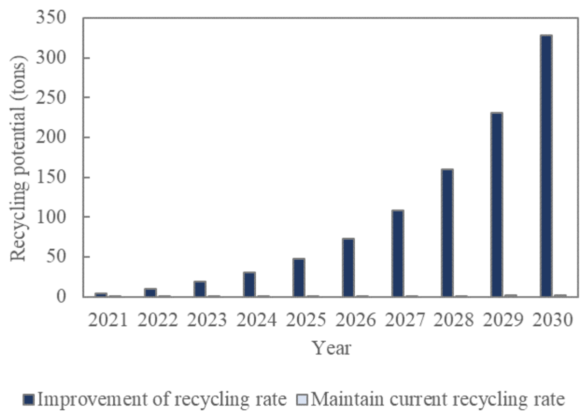

Fig. 3. Recyclable amount of lithium [tons].

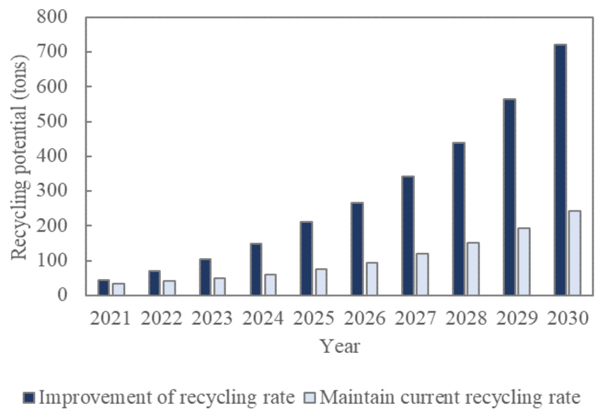

Fig. 4. Recyclable amount of cobalt [tons].

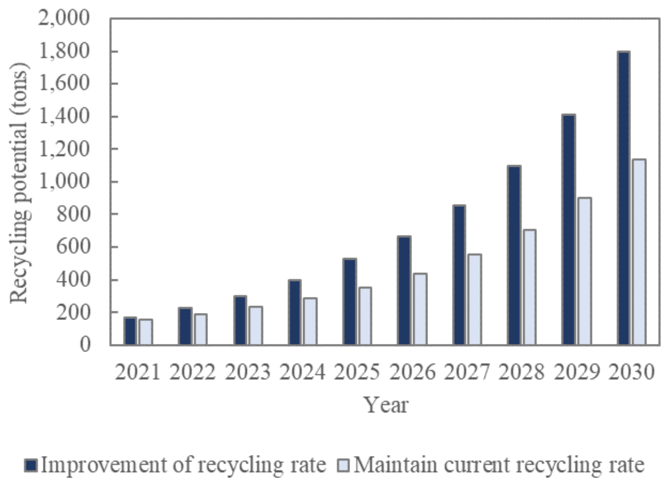

Fig. 5. Recyclable amount of nickel [tons].

4. Conclusion

This study focused on rare metals (lithium, cobalt, and nickel) and estimated the number of ELVs using the Weibull distribution to evaluate the amount of available recyclable materials due to the spread of CEVs.

The results suggest the following:

- Although GVs accounted for a high percentage of the predicted total number of ELVs after 2021, the number of CEVs is also expected to increase gradually. In particular, the number of HEVs scrapped is expected to increase from approximately 400,000 in 2021 to 1.1 million in 2030.
- In the improvement of the recycling rate scenario, the amount of rare metals that can be recycled is expected to increase from approximately 220 tons in 2021 to 2,900 tons in 2030 due to the increase in the number of scrapped CEVs, which have a high content of rare metals. Given that the total amount of rare metals recycled by all industries in 2019 was approximately 305 tons, this would be a significant increase.
- In the maintain current recycling rate scenario, the recyclable amount of rare metals in 2030 was projected to be approximately 1,400 tons. Although this result is an increase from the recycling volume in 2019 due to an increase in the number of CEVs scrapped, the recyclable volume has decreased significantly compared with the improvement of the recycling rate scenario.
- This difference in recycling volume is expected to affect the production potential of approximately 25,000-45,000 BEVs in 2030. In particular, the current recycling rate of lithium is low, which could become a bottleneck for BEV production.
- Further cooperation between the arterial and venous automobile industries will be necessary to increase the amount of recycled materials and maximize their utilization.

This study focused on rare metals and evaluated their recycling potential. Compared with previous studies, the study showed the importance of recycling not only copper but also rare metals used in batteries and other parts. The study also considered the extent to which the production of CEVs would be affected by changes in the recycling rate. The model used in this study provides valuable insights for evaluating and analyzing the feasibility of introducing CEVs from the perspective of metal resources.

In this study, the future recycling rate was set based on the European Union's proposed battery regulation [10], but the technical feasibility of recycling has not been sufficiently examined. It should be noted that there are uncertainties in parameters such as recycling rate, depending on future technological developments.

Future works could include applying this model to other metal resources and designing and evaluating a system to promote recycling based on technical feasibility. Another future task is estimating the primary supply, demand, and shortages of rare metals by extending this model.

Conflict of Interest

The author declares no conflict of interest.

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