Towards the efficient recycling of alloying elements from End of Life Vehicle steel scrap

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Abstract

There has been a sharp increase in the production of automobiles over the past decade. In 2010, one billion automobiles were in circulation worldwide. The automobile industry is one of the largest metals consumers and plays an important role in their sustainable use. Steel materials, including alloy steels that contain alloying elements (AEs) such as manganese, chromium, nickel, and molybdenum, are the main component of automobiles. The recycling of end-of-life vehicles (ELVs) significantly affects the cycling of iron, steel, and AEs. Currently, ELV recycling is performed using the electric arc furnace (EAF). In this method, losses of AEs are likely to occur because their presence is rarely considered. This study evaluated the environmental and economic benefits of alternative ELV recycling schemes, which allow more efficient utilization of AEs found in ELV-derived steel scrap (ELV-dSS). The AE contents in ELV-dSS (as car-parts) were estimated by means of a waste input-output material flow analysis (WIO-MFA) model extended for the detailed analysis of automobile composition. Using Japanese data, it was found that sorting ELV-dSS by parts can result in a significant recovery of AEs; more specifically, a 10-fold saving in AEs was achieved by sorting exhaust parts. The recoverable mass of AEs from sorted ELV-dSS was found to correspond to 8.2% of the annual consumption of AEs in Japan, as virgin resources in EAF steelmaking. ELV-dSS sorting was found to be significantly effective in the conservation of AE resources.

Keywords: End-of-life vehicle; alloying element; scrap steel; metals recycling; electric arc furnace; waste input-output material flow analysis

1 Introduction

The proficient management of resources is indispensable for realizing a sustainable society. Metals are considered as essential resource in the modern society, and their efficient use is a key for sustainable development (Gaustad et al., 2011; Graedel et al., 2012; Reck and Graedel, 2012). Reck and Graedel (2012) noted that the recycling of metals from end-of-life (EoL) products has become more complicated and challenging due to the complex structure and composition of contemporary functional products. Metals are typically used in combination and/or alloyed with other products. Unintentional alloying and dissipation may occur as a result of the thermodynamic properties of metals in recycling (Nakamura et al., 2011; Ohno et al., 2014). Efficient recovery of metals from EoL products requires careful deliberation of the recycling methods (Reck and Graedel, 2012).

The automobile industry is one of the largest metal consumers (Nakajima et al., 2013; Nakamura et al., 2011; Ohno et al., 2014). The production of automobiles has been increasing with global population growth. The International Organization of Motor Vehicle Manufacturers (OICA) estimated that by 2010, there were one billion automobiles worldwide (International Organization of Motor Vehicle Manufacturers (OICA), 2012). Thus, the automobile industry plays a vital role in the sustainable use of metals. The main component of automobiles is steel materials; therefore, the recycling of end-of-life vehicles (ELVs) could significantly affect the cycling of iron and steel.

There have been many studies regarding the material flow analysis (MFA) of iron and steel (Daigo et al., 2007; Michaelis and Jackson, 2000; Mueller et al., 2006; Pauliuk et al., 2012; Wang et al., 2007). The studies have mainly been concerned with the quantity-based flow and cycling of iron and steel, highlighting the importance of steel recycling in terms of the depletion of high-grade iron ore and CO₂ emission reductions. On the other hand, some recent studies have correctly identified the need for quality assurances, in order to guarantee sustainable material cycles for iron and steel (Hatayama et al., 2014; Nakajima et al., 2013; Nakamura et al., 2011; Nakamura et al., 2012; Pauliuk et al., 2012; Reck et al., 2010).

Owing to the complex usage of metals in automobiles, several problems have been identified in the recycling process of ELV-derived steel scrap (ELV-dSS). The most typical problem is the mixing, and contamination, of other metal materials into ELV-dSS. In the current basic ELV treatments, the non-reusable parts (e.g. air-conditioner coolants and airbags), copper contaminated sources (e.g. wire harnesses), and the reusable components (e.g. the engine) are removed, while the rest of the parts are shredded together to reduce the volume of scrap (Ohno et al., 2014). After shredding, non-ferrous metals are magnetically separated from ferrous metals; the magnetic ferrous materials are collected as carbon steel and recycled as an iron source for electric arc furnace (EAF) steelmaking. Copper removal is an important step in the ELV treatment as it is one of the most concerned contaminants in the recycling of steel: Copper has adverse effects on the workability of steel materials and has an accumulative tendency as the cyclic use of steel depending on thermodynamic distribution during steel recycling (Daigo et al., 2005; Hatayama et al., 2014; Houpert et al., 1997; Nakamura et al., 2011). If ELV-dSS contains a known concentration of copper, it must be diluted to below regulatory limits by adding pure iron during the EAF steel recycling process (Hatayama et al., 2014; Nakamura et al., 2012). Contamination in steel may also be caused by alloying elements (AEs), such as chromium (Oda et al., 2009), which are added to enhance certain properties of steel materials. These AE-enriched steel materials are known as alloy steels, and the various available types are consumed in large quantities by the automobile industry (Nakajima et al., 2013). Although AEs are intentionally added to produce alloy steels, they are a source of contamination in the recycling process. They are often considered unwanted constituents (International Organization for Standardization (ISO), 1987). Furthermore, some AEs tend to oxidize into steelmaking slag, depending on their thermodynamic distribution (Nakamura et al., 2011). In these cases, AEs are dissipated, representing the loss of an otherwise potentially valuable resource (Nakamura et al., 2012).

Alloy steel materials are often present in large quantities in automobiles. For example, high-tensile steels are used in the vehicle frame and stainless steels are used as exhaust parts. AEs are likely to be lost during current ELV recycling, which involves shredding and mixing car-parts of varying composition (Ohno et al., 2014). A solution proposed for this problem is the design of recycling-oriented automobiles,

which incorporate the metal combinations that cause less contamination during recycling into their design, in accordance with the thermodynamic distribution tendencies of the metals (Castro et al., 2004; Froelich et al., 2007; Millet et al., 2012). However, this solution does not take into account scrap from conventional vehicles, for which materials cannot be easily recycled separately. Therefore, an appropriate treatment process for efficient ELV-dSS recycling must be developed (Ohno et al., 2014).

Nakamura et al. (2012) estimated that significant reductions in CO₂ emissions could be achieved by preventing copper contamination in ELV-dSS and reducing the need for the dilution of copper by the addition of pure iron. Current recycling methods of ELV-dSS operate under strict precautions for the prevention of copper contamination. ELV-dSS with low concentrations of copper has been recycled as an iron source in the EAF steelmaking process (Matsubae et al., 2014a). On the other hand, little, if any, attention has been paid to AE concentrations in current ELV-dSS treatments (Ohno et al., 2014). Recent studies have highlighted the importance of developing an efficient recycling system that prevents the loss of indispensable AEs (Nakajima et al., 2013; Nuss et al., 2014; Ohno et al., 2014). Given the difficulties of removing AEs from the steel matrix under present technological and economic conditions, this study aimed to propose a process of disassembling and collecting parts with similar compositions to minimize losses of AEs, and then evaluate the efficiency of the proposed sorting approach.

This study consists of two parts: first, the AE contents in automobiles and ELV-dSS are estimated by extending the waste input-output material flow analysis model (WIO-MFA model); second, the efficiency of ELV-dSS sorting is evaluated. The WIO-MFA model is a useful top-down approach for estimating nationally averaged material composition of various products (Nakamura and Nakajima, 2005; Nakamura et al., 2007). Japanese data were selected due to the availability of high-resolution input-output (IO) data in terms of metals, while the model itself is applicable to any economy. However, even for Japanese IO data, the resolution is not high enough to allow the material composition estimation of individual automobile parts and components (Nakajima et al., 2013; Ohno et al., 2014). To cope with this problem, substantial disaggregation and rearrangement of automobile related sectors was conducted for the Japanese IO data. This resulted in the highest-resolution IO-based estimates ever available for AE

contents of automobile parts and components. Development of this information base enables us to evaluate the AE saving potential and benefits of sorting ELV-dSS.

2 Method and Data

2.1 WIO-MFA

WIO-MFA enables the estimation of the flow of individual materials associated with the flow of commodities by assessing the material composition of commodities based on IO analysis. Using the IO table adjusted for MFA, the material composition matrix C_{MP} can be calculated using Equation (1).

$$C_{MP} = \tilde{A}_{MP}(I - \tilde{A}_{PP})^{-1} \quad (1)$$

Here, (i, j) element of $\tilde{A}_{MP}$ and $\tilde{A}_{PP}$ represent the coefficient of input i to produce one unit of output j accounting for yield losses during production processes, $\tilde{A}_{MP}$ denotes the input of materials (M) for the production of products (P), and $\tilde{A}_{PP}$ represents the input of intermediate products (P) for product production (P).

The (i, j) element of the matrix C_{MP} represent the volume of material i that comprises one unit of product j . Thus, the column sum of this matrix gives the mass of one unit of output when $\tilde{A}_{MP}$ is measured in mass. When the unit of a product is expressed physically, as one ton for instance, the column sum of the corresponding composition matrix is also one ton. When the product is expressed in monetary form, as one-million Japanese yen, the column sum of the corresponding composition matrix represents the mass per one-million Japanese yen. For further details on the methodology, see Nakamura et al. (2007).

In previous studies, a high-resolution WIO-MFA table for the simultaneous flow analysis of steel AEs was developed based on the Japanese IO table for 2000 and 2005 (Nakajima et al., 2013; Ohno et al., 2014). These models and data were extended to automobile-related sectors in the present study.

2.2 Disaggregation of the automobile industry into component sectors

Aggregated sectors in the IO table occasionally lead to unclear results. Since the car-parts sector is highly aggregated in the IO table for Japan (Ministry of Industrial Affairs and Communications (Japan), 2009), despite the extensive variety of parts, the different origins of the materials in each automobile part cannot be distinguished by the WIO-MFA. Thus, disaggregation of the car-parts sector in the IO table is necessary for a detailed analysis of the material composition and origins of materials in automobiles.

In the IO table for Japan, five sectors are directly related to the automobile industry. The passenger cars, trucks, buses, and other vehicle sectors are the final production divisions for automobiles given in the IO table. The intermediate sectors (motor vehicle body, engine, and car-parts) are designated as inputs to the final production sectors. The car-parts sector is disaggregated into ten categories: suspension, shaft, steering, electrical equipment, interior, transmission, brakes, exhaust, and body parts including others. Certain practices, such as direct inputs of steel materials to the passenger car sector, complicate the determination of the usage of steel materials. The flow of steel materials involving several routes was consolidated by imposing mass balance across all automobile-related sectors. The WIO-MFA table developed in previous studies includes information on the total input of steel materials into the automobile industry (Nakajima et al., 2013; Ohno et al., 2014). By fixing the mass balance of steel material inputs, the uses of steel materials in the production of each component were allocated based on car-part composition data (Japan Environmental Sanitation Center, 2009; Tasaki et al., 2004) and the steel and metal material usage in each part (Special Steel Association of JAPAN, 2002). The detailed procedure of data assembly is included in the appendix. Owing to the lack of detailed information

regarding the inputs of non-metals, energy, and services to produce each part, these inputs were assigned according to the quantity of each part produced (Japan Auto Parts Industries Association, 2007). Although the use of national IO data results in the WIO-MFA model providing the national average composition of products, published practical sampling data for several types of automobiles were utilized for sector disaggregation. Although the use of data from different sources may introduce further uncertainty into the analysis results, it would serve as a useful benchmark for AE content in car-parts given the paucity of published information on this subject.

3 Results and Discussion

3.1 Testing and statistical analysis

The results generated by the proposed model are compared with actual production statistics. The WIO-MFA findings for the passenger car sector estimated that the total mass of passenger cars was 770 kg per one million yen. The mass of each class of engine displacement (under 660 cc, between 660 and 2,000 cc, and over 2,000 cc) was calculated as 639, 943, and 1,716 kg by multiplying the respective unit prices, according to the actual production results indicated in Table 1. The masses of the tires, window glass, and natural fibers were not included in the results, as only metals and plastics were selected as target materials in the WIO-MFA. Further information regarding the definition of the sectors was reported in our previous study (Ohno et al., 2014).

Table 1: Production volumes, value, and unit price of passenger cars in Japan in 2005, subdivided by engine capacity (Ministry of Industrial Affairs and Communications (Japan), 2009).

Engine displacement	<660cc	660–2,000cc	>2,000cc	Total
Production (units)	1,408,753	3,411,609	4,196,373	9,016,735
Value (million yen)	1,169,871	4,178,641	9,352,545	14,701,057
Unit price	0.830	1.225	2.229	1.630

(million yen/unit)

Compared with sales results from 2005 in Japan, the calculated results for the total mass of passenger cars are in agreement with the real products (Fig. 1). Although the model years of the three samples (indicated by rhombic symbols) differ from those of the analyzed results, they showed similar trends in the WIO-MFA results of each engine displacement.

Figure 1: Relationship of total mass of a car and engine displacement for the top 10 cars sold (Japan Automobile Dealers Association, 2005) and the correlation with the results of the waste input-output material flow analysis. The same color marks describe the max and minimum engine displacement and mass for the different grades of the same type of a car. Samples 1 to 3, represent the practical sampling

results for a light passenger car produced in 1996 (Matsubae et al., 2014a), a middle class passenger car in 1993 (Ministry of Environment (Japan), 2012), and a high class car in 2002 (Japan Environmental Sanitation Center, 2009), respectively.

The results of comparing car-part compositions in the three samples show good overall correlation (Fig. 2). However, as the composition of the parts represents the average of all classes of passenger cars, it does not reflect the detailed differences among the classes. For instance, high-class cars with larger engine displacement (Fig. 2, sample 3) tend to use more aluminum parts (Ducker Worldwide, 2012; European Aluminium Association, 2008). Additionally, the classifications of car-parts differ by publication. These disagreements, caused by averaging and inconsistent classification, should be considered a limitation of the analysis. In this study, to simulate averaged ELV-dSS composition, the estimated car weight of middle class passenger cars (660-2,000 cc, 943 kg), which have the highest sales in Japan (Japan Automobile Dealers Association, 2005), is used as the reference sample for car composition.

Figure 2: Car-part composition percentages in passenger cars for three samples and estimated results.

Waste input-output material flow analysis (WIO-MFA).

3.2 AE compositions in different parts of ELV scrap

Figure 3 illustrates the car-part compositions of a middle class passenger car obtained by WIO-MFA. The unit mass of the passenger car was determined as 943 kg, excluding tires and glass. The amounts of manganese, chromium, nickel, and molybdenum in one passenger car are 3.62, 6.35, 1.50, and 0.19 kg, respectively. The exhaust, which accounts for 3.4% (31.9 kg) of the total mass of a passenger car, contains large amounts of AEs owing to the use of stainless steel. These are 3.00, 0.71, and 0.06 kg of chromium, nickel, and molybdenum, respectively.

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Figure 3: Car-part composition percentages in a passenger car unit, with the associated concentrations of alloying elements as obtained by waste input-output material flow analysis. (a) details the composition of the parts and components, while (b) gives the percentages of AEs in the corresponding parts. The AEs studied are manganese, chromium, nickel, and molybdenum. The “parts from other industries” category includes all the intermediate products (i.e., those not produced by automobile-related sectors) used in the production of a passenger car.

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The typical ELV treatment in Japan involves the shredding and pressing of the car-parts remaining after the removal of copper and reusable parts such as doors (Ministry of Environment (Japan), 2012; Nakamura et al., 2012; Ohno et al., 2014). Based on the records reported by a Japanese disassembling company (Ministry of Environment (Japan), 2012), it was assumed that the treatment conditions resulted in 100% of the engine and large copper containing parts (parts from other industries and electric equipment) being removed, and 25% of the body and interior parts reused and/or recycled. Furthermore, to ship ELV scrap as separated ELV-dSS, it was assumed that treated ELV scrap was shredded separately, part by part, with only steel related metals (iron, AEs, and zinc) remaining for magnetic separation by considering the necessity of volume reduction and removal of non-ferrous and non-metal materials from ELV-dSS. For simplicity, other forms of contamination from sorting errors and/or non-magnetic material were not accounted for, nor were the possible losses during shredding and scrap collection. On the other hand, austenitic (Cr-Ni) stainless steel was included in the analysis. With these assumptions applied to the estimated the passenger car mass (943 kg/unit) and car-part composition, the total mass of the ELV-dSS was estimated as 487 kg, with 2.26 kg of manganese, 4.18 kg of chromium, 1.16 kg of nickel, and 0.12 kg of molybdenum. The average concentrations of manganese, chromium, nickel, and molybdenum by mass of ELV-dSS were estimated to be 0.46, 0.86, 0.24, and 0.02%, respectively. These concentrations of AEs represent the composition of mixed ELV-dSS without sorting. The concentration of AEs differs among car-parts (Fig. 4), indicating that mixing will result in diluting the higher concentrations of some parts with the lower concentrations of other parts. Exhausts are characterized by high concentrations of chromium, nickel, and molybdenum (10.10, 2.37, and 0.20% respectively), because of the use of stainless steel. The manganese concentration in the suspension (0.72%) is higher than the average concentration in ELV-dSS. Similarly, parts with lower AE concentrations, such as the body and brakes, are contaminated through mixing with high AE concentration parts. Consequently, the mixing of different parts can cause loss in quality of both AEs and steel (Nakamura et al., 2012). Some AEs (such as manganese and chromium) in mixed ELV-dSS transferred to EAFs oxidize easily and form slag (Nakajima et al., 2011). While other AEs that tend to remain in molten steel (such as nickel and molybdenum) are diluted with

primary iron to meet quality requirements (Nakamura et al., 2011). Consequently, the recycling of mixed ELV-dSS is likely to cause material losses of AEs and dilution losses of iron as well (Ohno et al., 2014).

Figure 4: Mass of the treated ELV-derived steel scrap by parts and the concentrations of alloying elements. Y-axes of the graphs have the same units, but the scales are different for each alloying element.

The results suggest that switching from the current practice of mixed treatment to sorting by parts can reduce AE losses. Accordingly, producing secondary steel materials from sorted ELV-dSS with

similar alloy compositions can reduce the consumption of virgin sources of AEs, such as ferroalloys. Applying estimated ELV-dSS composition to the 2005 actual recycled scrap volumes in Japan (2,348 kt), the mass of each scrap part and their accompanying elements can be estimated (Table 2). Adding the mass of removed parts, the total mass of treated ELV was estimated as 4,548 kt. Considering the mass of one unit of automobile in this study (943 kg), the number of discarded ELVs was estimated as 4.8 millions. Since around four to five million units of ELVs are discarded in Japan every year (Tasaki et al., 2004), it can be said that the assumptions for ELV treatment conditions in this study are not far from the reality in terms of mass. The total amount of AEs contained in 2,348 kt of recycled ELV-dSS correspond to 10.5% of the amount of virgin AEs annually consumed in EAF crude steelmaking (Ministry of Economy, Trade and Industry (Japan)2006). Despite the considerable amount of AEs contained in ELV-dSS, about 93% of ELV-dSS is currently recycled to carbon steels that require lesser amounts of AEs than alloy steels produced by the EAF steelmaking process (Ohno et al., 2014). Therefore, the present recycling of ELV-dSS is inefficient when it comes to the use of AEs.

A caveat to the above result is the disregard of the time lag between the production and the end of lifetime. As Nakamura et al. (2014) stated, the materials contained in products are serially recycled according to the lifetime distribution of products. The results above were obtained by assuming that the composition of all ELV-dSS recycled in 2005 is equal to the composition of cars produced in 2005. This is a strong assumption that disregards any possible changes in material composition, weight, and type of cars over time. Relaxation of this strong assumption would require a dynamic extension of the current framework, including possible changes in car composition over time, which is an important direction for future research.

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274 Table 2: Estimated amounts of treated scrap by parts, in 2005, and their composition of alloying elements.

	Scrap mass (kt)	Alloying elements (t)			
		Mn	Cr	Ni	Mo
Body	1,424	6,608	2,680	1,230	149
Suspension	194	1,403	436	113	27
Shaft	185	779	1,324	376	68
Steering	139	502	470	191	23
Interior	93	471	138	54	3
Transmission	96	342	479	204	22
Brakes	72	132	52	18	2
Exhaust	144	662	14,562	3,415	289
ELV-dSS total	2,348	10,898	20,141	5,600	583
Removed	2,200	6,892	10,608	1,660	324
Total	4,548	17,790	30,748	7,260	907

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3.3 Scrap sorting to prevent the loss and dilution of AEs

Prevention of AE dissipation in ELV-dSS recycling calls for appropriate scrap sorting. Here, a simple ELV-dSS sorting scenario is considered, sorting ELV-dSS into three types of scrap, A, B, and C. Suspension parts are sorted into Scrap A to retain their high manganese content. Exhaust parts, which are characterized by the highest concentration of chromium, nickel, and molybdenum, are sorted as Scrap B. The remainder of the parts is considered Scrap C. This simple sorting process was found to be effective in reducing both the dilution of AEs and the contamination of iron (Fig. 5). Figure 5 shows the ratio of AE concentrations contained in each of the three scrap categories to the averages of mixed scrap without sorting, defined as the concentration ratio. It confirms the effects of sorting on concentrating AE (above 1) and purifying iron matrices (less than 1). Sorting Scrap A resulted in about a 1.5-fold concentration of manganese, but no significant purification of iron matrices. The latter can be attributed to the wide range usage of manganese in the steel materials for automobiles. On the other hand, sorting of Scrap B was found to result in significant concentration of 10-fold for chromium, nickel, and molybdenum.

The three scrap categories are defined in a straightforward fashion and can be applied rather easily to the practice of steel making. Scrap A would be suitable for manganese requiring steel, such as spring steel (International Organization for Standardization (ISO), 2004), which is composed of 0.6 to 1.0% of manganese. Scrap B would be appropriate for austenitic (nickel containing) stainless steel requiring higher concentrations of chromium and nickel. In addition, because some separated parts contain higher concentrations of AEs, Scrap C is less contaminated (Fig. 5). Thus, EAF steelmakers can use Scrap C as a high-grade iron source for various grades of steel production. Although the concentration of manganese is not significantly changed by scrap sorting, manganese contained in scrap can work as both AE and a deoxidizing agent in steelmaking (Nakajima et al., 2008; Nakamura et al., 2011).

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Figure 5: Improvements in alloying elements purities by scrap sorting into three categories (A, B, and C).

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304 Prior to sorting, the percentages of chromium and nickel in ELV-dSS were 0.86% and 0.24%,
 305 respectively. The summed concentration of chromium and nickel cannot exceed 0.35% for some low-
 306 alloyed steel materials (International Organization for Standardization (ISO), 1987). Approximately 5,000
 307 kt of other iron sources are required to dilute the chromium and nickel contained in 2,348 kt of mixed
 308 ELV-dSS to achieve the target concentration. This means a significant loss of quality for iron (Nakamura
 309 et al., 2012). In contrast, the sorted Scrap C would require minimal dilution because the summed
 310 concentration of chromium and nickel is 0.36%. The practical recyclability of Scrap C, requiring less

dilution with iron, would be significantly beneficial in terms of the reduction pig iron production and the associated energy requirements and CO₂ emissions.

3.4 Virgin resource saving potential and its effect for environment and economy

Table 3 presents the estimated amounts of AEs that can be substituted for virgin resources. Further to the discussion in Section 3.3, the entire manganese content of ELV-dSS was assumed recoverable. For other AEs, only Scrap B mass compositions were considered recoverable.

Table 3: Recoverable amounts of AEs from ELV-dSS and equivalent amounts of ferroalloys.

Virgin resource saving		Mn	Cr	Ni	Mo	Total
Recoverable mass (t)		10,898	14,562	3,415	289	29,163
Recovery ratio (%) ^a		100	72	61	50	78
Corresponding to annual consumption in EAF (%) ^b		10.0	7.6	7.7	3.5	8.2
Contents in ferroalloy (%)	Average ^c	78	57	28	62	
	Lowest ^d	73	55	16	55	
	Highest ^d	85	70	28	70	
Ferroalloy equivalent (t)	Average	13,971	25,547	12,197	466	52,181
	Lowest	14,928	26,476	21,344	525	63,274
	Highest	12,821	20,803	12,197	412	46,233

a: Percentage of recovered AE mass / AE contained in ELV-dSS

b: Percentage of recovered AE mass / annual consumption of AE in Japanese EAF in 2005

c: Japan Oil, Gas and Metals National Corporation (JOGMEC), 2007

d: ISO 5446 (1980), ISO 5448 (1981), ISO 6501 (1998), ISO 5452 (1980)

Figure 6 gives the estimated amounts of greenhouse gas (GHG) emissions and imports of virgin AE resources that result from the proposed sorting procedure. It was estimated that a total of 318 to 609 kt-CO₂ eq of emissions can be reduced in the production of ferroalloys, which corresponds to 8.6% to 16.4% reduction in the emission from ferroalloy production in Japan. The total saving for electricity and fuel-derived energy were also evaluated as 212 to 319 GWh and 1,641 to 2,265 GJ, respectively, which correspond to 7.6% to 11.4% of electricity and 5.8% to 8.1% of fuel-derived energy for ferroalloy production in Japan (Agency for Natural Resource and Energy, 2005). The amount of ferroalloys recovered corresponded to 5.0% of all imported ferroalloys in 2005 (Ministry of Industrial Affairs and Communications (Japan), 2009), which represents a saving of about 13 billion yen. These results represent the non-negligible contribution of efficient ELV-dSS recycling to both the environment and economy, despite the modest 6.8% share of ELV-dSS in purchased steel scrap (The Japan Ferrous Raw Materials Association, 2006).

Figure 6: Potential reductions in (A) greenhouse gas emissions, imports, and (B) electricity and fuel-derived energy, due to the decrease in the use of virgin resources following appropriate ELV-dSS utilization. Error bars indicate the variability between highest (bottom) and lowest (top) alloying element concentrations in ferroalloys. For molybdenum, data was not available from Haque et al., 2013. a: Inventory Database for Environmental Analysis, Japan; b: Mixed fuel (mainly hydro-power, gas, and coal) electric generation, Tasmania, Australia; c: Australian average (mainly coal and gas fuel) electric generation, Australia; d: Trade Statistics of Japan.

4. Discussion and conclusion

This study has shown the considerable potential of ELVs as secondary sources of material. Efficient utilization of ELV-dSS by sorting will play an important role in resource dissipation prevention and conservation. It was found that the introduction of a rather simple sorting scheme for ELV-dSS, containing three parts (suspension parts, exhaust parts, and others), can be beneficial for the environment and the economy. This finding gives an alternative option for ELV recycling that focuses on the use of the AE content, which differs from previous recycling schemes that regard ELV-dSS as an iron source (Matsubae et al., 2011; Simic and Dimitrijevic, 2013). Furthermore, a variety of scrap compositions can be obtained under different ELV treatment scenarios, based on the national average automobile composition. Utilizing the features of the model, a useful comprehensive decision can be made to support policy makers and ELV treatment stakeholders. Considering the average lifetime of automobiles (Hatayama et al., 2010), many automobiles produced in 2005 will not reach EoL and be discarded until several years later. Since the model simulated the scrap composition of automobiles produced in 2005, the results would also be useful for estimating the requirements of ELV recycling in the near future.

Appropriate ELV-dSS utilization, based on sorting, has significant potential for cost savings and virgin material import reduction. This may motivate ELV treatment stakeholders and EAF steelmakers to use appropriately sorted ELV-dSS. However, this form of ELV treatment has rarely been implemented in practice (Froelich et al., 2007; Japan Environmental Sanitation Center, 2009; Matsubae et al., 2014a; Matsubae et al., 2014b).

In our previous study, potential obstacles for the implementation of scrap sorting were identified (Ohno et al., 2014) as gaps in knowledge and the attitude between steel production companies and ELV recyclers, and the absence of affordable efficient sorting technologies. The results of this study can provide some solutions to these issues. For ELV recyclers, sorting the ELV scrap into the three proposed categories would be easy, without the need for detailed information about the material compositions or

substantial additional investments in the facility. It also enables steelmakers to use ELV-dSS with relative ease, using a basic level of understanding of the standard AE contents in ELV-dSS.

Another obstacle identified in the previous study was the problem of the steel scrap market, which poses a challenge to the implementation of the scrap sorting methodology proposed in this study. In the current market, scrap is classified and traded almost exclusively based on its shape with almost no consideration of the value of its alloy content (European Ferrous Recovery and Recycling Federation, 2007; Institute of Scrap Recycling Industries (ISRI), 2013; The Japan Ferrous Raw Materials Association, 2008). This situation in the scrap market is likely to discourage ELV recyclers from sorting ELV-dSS on the basis of AE composition (Matsubae et al., 2014b). The amount of AEs present in automobiles is likely to increase with the current trends in the automobile industry (The Japan Iron and Steel Federation, 2013). Coping with this trend of increasing AE content in ELV-dSS, while incorporating sustainable resource use, would call for revisions to scrap grade definition and pricing in the scrap market. Scrap pricing based on AE content would be beneficial to ELV recyclers and encourage them to engage in ELV-dSS sorting.

In the present study, the sorting, recycling, and utilization objectives were selected according to the AE concentration of each scrap and steel material in a straightforward manner, without resorting to a systematic optimization algorithm, such as the minimization of virgin-resource use, the environmental impact, and/or cost reduction (Kondo and Nakamura, 2005). AEs differ in terms of resource availability, environmental loads in mining and production, and the value of the resources and materials. The use of different optimization objectives would result in different patterns of optimal sorting. Extending the current model along these lines is an important direction for future research.

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Appendix. Data preparation for the disaggregation of automobile sectors in the IO table

In previous studies on the WIO-MFA model, the hot-rolled special steel sector was disaggregated into 19 sector grades (Nakajima et al., 2013; Ohno et al., 2014). Here, “special steel” is defined as the steel added specific properties, including alloy steel. In the previous disaggregation process, the total input amounts of every grade of steel related to automobile sectors were fixed (as shown in the left bars of each sector in Figure A1). There were two problems to be addressed: (1) direct inputs to the final product sectors (passenger car sector, and the bus, truck, and others sector) made the steel material usage unclear; and (2) composition of disaggregated special steel inputs into each sector were the same. In addition to solving these problems, disaggregation of parts sector was carried out in this study.

As shown in Figure A1, the direct inputs of steel materials into the final product sectors were only allocated to the parts sectors; the input amounts to the body and engine sectors were unchanged. This means that direct inputs of steel materials to final products were assumed to be indirect inputs to final products in some parts. Through this process, problem (1) was solved and all steel usage in automobiles could be traced. The process for solving problem (2) was operated simultaneously with parts sector disaggregation. Since the body and engine sectors have already been separated, the specific steel usages in these sectors were fixed before the parts sectors. The Special Steel Association of JAPAN (2002) provided relatively detailed information on steel usages and masses in automotive engines. Based on this reference, some grades of special steels such as free-cutting, heat-resistant, and structural steels were fixed as engine inputs. Only high-tensile steel and small amounts of weathering steel were allocated to the body sector, since it does not demand large amounts of special steels. The remainder of the special steels,

403 not distributed to the engine and body sectors, were allocated to 10 types of parts based on the reference
404 information (Special Steel Association of JAPAN, 2002).

Figure A1: Comparison of steel material inputs for each automobile related sector (1) before and (2) after the disaggregation process.

405

406 There was some discrepancy between the total steel demand for parts reported in the reference and

407 the total steel supply reported in the IO table. Since the reference reported the average special steel

408 content in each component of one automobile unit, the steel demand in the parts sectors was estimated by

409 multiplying the number of automobiles produced in 2005 (Table1) and the inverse of the yield ratio of

410 car-parts sector applied in WIO-MFA. The calculated steel demands and the IO based supply were

411 subsequently harmonized by allocating surplus and shortage. More specifically, for structural steels

412 (carbon and alloy), the surplus was allocated to the “parts for body and others” sector. These data
413 adjustments resulted in some changes in the composition of special steel in each of the components
414 (Figure A2).

Figure A2: Allocated special steel composition in disaggregated-part sectors

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