Hybrid LCA of a Design for Disassembly Technology: Active Disassembling Fasteners of Hydrogen Storage Alloys for Home Appliances

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In the current recycling system of end-of-life (EoL) appliances, which is based on shredding, alloying elements tend to end up in the scrap of base metals. The uncontrolled mixing of alloying elements contaminates secondary metals and calls for dilution with primary metals. Active disassembling fastener (ADF) is a design for disassembly (DfD) technology that is expected to solve this problem by significantly reducing the extent of mixing. This paper deals with a life cycle assessment (LCA) based on the waste input–output (WIO) model of an ADF developed using hydrogen storage alloys. Special attention is paid to the issue of dilution of mixed iron scrap using pig iron in an electric arc furnace (EAF). The results for Japanese electrical and electronic appliances indicate superiority of the recycling system based on the ADF over the current system in terms of reduced emissions of CO_2. The superiority of ADF was found to increase with an increase in the requirement for dilution of scrap.

Introduction

Since the introduction of the home appliance recycling law in the year 2001, around 13 million units (5×10^9 kg) of end of life (EoL) electrical and electronic appliances (TV sets, air conditioners, washing machines, and refrigerators) are being collected for recycling per year in Japan (*1*) (henceforth, the term EEE is used to refer to electrical and electronic appliances, and the term WEEE is used to refer to EoL EEE). As of 2008, the overall rate of recycling (only items with a commercial value to the generator are included) was around 83% (*1*). The current recycling system is to a large extent based on shredding, and metals are recovered in the form of scrap of base metals (iron, copper, aluminum). Iron, however, is used in EEE not simply just in the form of iron, but in diverse forms of steel products, which differ from each other in composition, such as nonferritic (austenic) (CrNi) stainless steel, ferritic (Cr) stainless steel, high-speed steel, and electromagnetic steel. While the same applies more or less to other base metals as well, in this study we focus on iron-based materials.

Hidden behind the seemingly satisfactory performance of the current recycling system is the fact that most alloying elements such as Cr and Mo are dissipated into recycled base metals in an uncontrolled manner (*2*). For example, ferritic stainless steel with 13–18% (wt%) of Cr cannot be separated from other iron-based materials by magnetic separation and therefore ends up in iron scrap mixed with other iron-based materials. This scrap is used in electric arc furnaces (EAFs) to produce low-grade products such as bar steel used for construction. According to ref *3*, only around 30–35% of ferritic stainless steel is recovered as stainless steel in Japan. Once the Cr portion ends up in construction steel, it cannot be recovered (*4*). In other words, alloying elements get dissipated irreversibly.

Two environmental consequences arise from the mixing of alloying elements with base metals. The first and obvious one is the loss of scarce alloying elements, the production of which requires considerable amounts of energy and resources. The second one, presumably less obvious, is that the mixing of alloying elements with base metals in an uncontrolled manner contaminates the scrap and reduces its quality. While alloying elements are highly valuable (essential ingredients of high-quality steel products) when mixed in a controlled manner, they can become contaminants when mixed otherwise, which is the case for scrap generated from the current recycling system based on shredding. Currently, the recovered low-quality secondary metals (scrap) are diluted with primary metals (pig iron) to meet the quality requirement of EAF products (*5*). For stainless steel products, Figure 1 presents the factor by which a specific type of stain steel scrap has to be diluted so that it can be used for fabricating a thin carbon steel sheet, the Cr content of which should be less than 0.20%. In the case of SUS 430 (Cr) stainless steel (one of the most widely used types of stainless steel for EEE), for instance, it can be as high as 85 (in Japan, the AISI grade number for stainless steels is preceded by SUS, e.g., SUS 430 corresponds to AISI 430).

Dilution with primary metals is not the only way to deal with the presence of uncontrolled alloying elements in scrap. By changing the operational condition of EAFs including secondary refining (total pressure, oxygen partial pressure, slag composition, temperature, etc.), some unwanted mixed elements can be transferred to either vapor or slag phase and removed from the liquid metal phase (*6*). However, this could be associated with a substantial loss of target products and an increase in the production cost. Furthermore, given the uncertainty regarding the chemical composition of scrap, changing the operational conditions could result in undesirable changes in the composition of products. Therefore, in many cases, dilution emerges as the only viable option. Henceforth, dilution will be regarded as the only available option to deal with the problem of mixing.

Disassembly plays a key role in determining the quality of materials and components recovered from EoL products (*7*). Design for disassembly (DfD) is concerned with product design strategies aimed at efficient disassembling of EoL products for the purpose of, among others, recovering components or materials of high quality such that they can be reused or recycled without significant loss in their original quality, instead of being down-cycled (*8*). Because the disassemblability of a product critically depends on fasteners, the selection of fasteners becomes an important factor in DfD (*8, 9*). Active disassembly is a nondestructive dismantling process based on fasteners made of "smart materials" which

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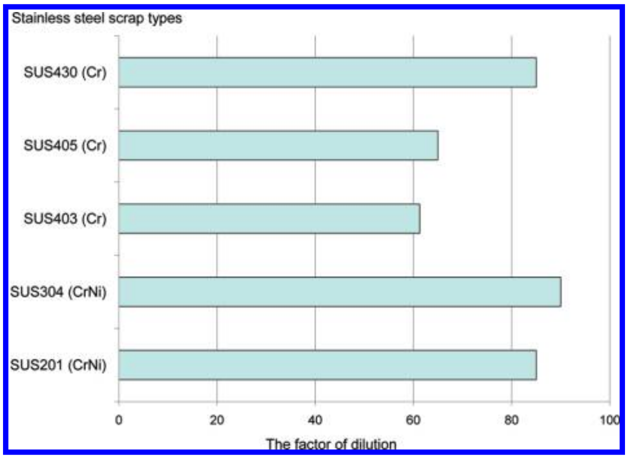

FIGURE 1. Amount of primary steel required for diluting different types of stainless steel scrap for use as a source for producing thin carbon steel sheet (kg/kg). Source: own calculations based on Japanese Industrial Standard (JIS) (see Table S1 of Supporting Information (SI) for details).

enable products to tear themselves apart or split open under specific conditions in the EoL phase (*10*).

This paper deals with a life cycle assessment (LCA) of DfD implemented using an active disassembling fastener (ADF) made of hydrogen storage alloys (developed by one of the authors) (*11*). Explicit consideration of the material composition and the disassembling process on the basis of detailed technical knowledge is a distinguishing feature of this study. Our analysis is based on the environmentally extended input−output model (EEIO) (*12, 13, 14*). This model was further extended, in accordance with ref *15*, to deal with specific issues considered in this study, including the flow of scrap and EoL processes. The need for an explicit consideration of EoL processes, waste/byproduct flows, and the economy-wide interaction between goods production and EoL processes/sectors makes this model, the waste input−output model (WIO), suitable for achieving the objective of this analysis.

Recycling System With and Without ADF

ADF and Its Activation. The ADF consists of an iron-based alloy including 6−10 atomic percent (at%) of "mischmetal", which is a mixture of rare earth elements such as cerium and lanthanum and is known as an affordable hydrogen storage alloy (*11*). Hydrogen storage alloy absorbs and desorbs hydrogen gas reversibly, and becomes brittle when it absorbs hydrogen. This feature causes the ADF to break into pieces when exposed to hydrogen gas at 4 MPa and 353−373 K (Figure S1 in the Supporting Information (SI)). In the disassembling process, after preheating to an appropriate temperature, WEEE with the ADF are placed in a sealed chamber, heated, and exposed to compressed hydrogen gas (Figure S2 of SI gives a schematic picture of the process), resulting in the brittle fracture of the ADF and the separation of the components fastened by the ADF. After evacuating the chamber, the separated components can be recovered. Henceforth, the term "ADF-hydrogenation process" is used to refer to this process applied to EEE with the ADF.

Current Process. The iron scrap recovered from WEEE by the current treatment process is generally a mixture of diverse iron components, which is usually used in EAFs to produce steel for construction. Consider the case where the iron components of WEEE, henceforth simply termed "the scrap", consist of alloy steel of the same grade (such as SUS 430 stainless steel) and carbon steel, with the mass of each given by m_α and m_c, and $m = m_\alpha + m_c$. The alloying elements present in the scrap are considered to be the contaminant.

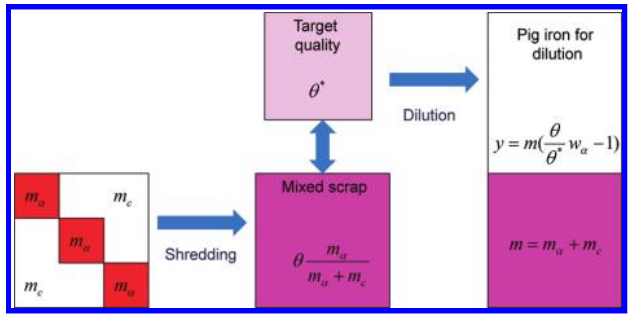

FIGURE 2. Use of iron scrap recovered by current EoL process in EAF. If the target quality θ^* (in terms of the degree of mixture of contaminating elements) is not met by the recovered scrap, that is, $\theta^* < \theta w_\alpha$, the scrap has to be diluted with pig iron, by an amount *y*, until the target quality is met. w_α refers to the proportion of m_α in the total mass, *m*.

Let θ be the composition of the alloying element of the largest composition in alloy steel, say, Cr in ferritic stainless steel such as SUS 430 and SUS 403, for which the composition of other alloying elements is negligible. For SUS 430 stainless steel, $\theta = 0.17$, and for SUS 403 stainless steel, $\theta = 0.1225$ (Table S1 of SI). The degree of mixing (contamination) by the alloying element in the scrap is given by

$$\theta \frac{m_\alpha}{m_\alpha + m_c} = \theta w_\alpha \tag{1}$$

where w_α refers to the composition of alloy steel in the scrap.

The degree of mixing that is acceptable as a feed for the EAF is subject to quality requirements of the EAF product. Denote by θ^* the (product-dependent) upper limit of the alloy composition that is acceptable for the target product of the EAF. If thin carbon steel is the target product, for instance, its maximum Cr composition determines the upper limit, which is $\theta^* = 0.002$ (Table S1). If $\theta^* < \theta w_\alpha$, the scrap has to be diluted to meet the quality requirement. For $\theta^* \le \theta w_\alpha$, the factor of dilution, η, is defined as

$$\eta = \frac{\theta}{\theta^*} w_\alpha \ge 1 \tag{2}$$

It is now clear that what is shown in Figure 1 is the dilution factor θ/θ^* for different types of stainless steel. It is 0.17/0.002 = 85 for SUS 430 stainless steel.

Let *y* denote the amount of pig iron needed for dilution:

$$y = m(\eta - 1) \tag{3}$$

where *m* is the iron mass of the scrap. The total amount of EAF steel to be produced to absorb the scrap, *z*, is then given by

$$z = m + y + \text{other additives} = m\eta(1 + \varepsilon) \tag{4}$$

where $\varepsilon \ge 0$ denotes the ratio of content of additives such as ferroalloys. Figure 2 shows a schematic representation of the recovery of scrap using the current process and its use in an EAF with possible dilution.

ADF-Hydrogenation Process Applied to EEE. Figure 3 shows a schematic representation of the recovery of scrap from WEEE with the ADF using the ADF-hydrogenation process and the use of the recovered scrap. No mixing of different iron components takes place in this case. Special steel components of high material value, such as alloy steel, can be reused as crude special steel. In terms of the concept of statistical entropy applied to material flow analysis (MFA), the dilution of scrap with primary metals corresponds to an increase in the entropy of mixing (*16*). The ADF can hence

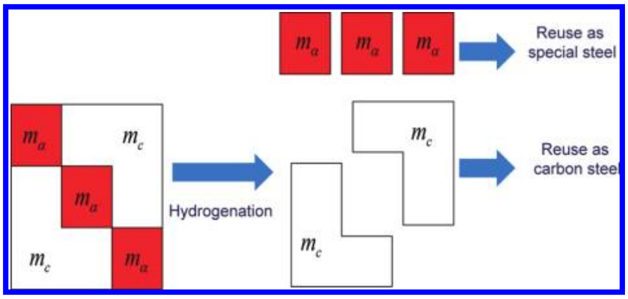

FIGURE 3. Use of iron scrap recovered by ADF-hydrogenation process based on activation of ADF. The scrap is recovered without mixing and, hence, can be reused or recycled (no down-cycling). If fed into an EAF, no dilution is needed.

be characterized as a technology that is aimed at preventing an increase in the entropy of mixing.

The EAF process. Iron scrap and pig iron are the primary materials that are used for steel production in an EAF process (some small amounts of ferroalloys are also used). Let the amount (kg) of pig iron and scrap used to produce 1 kg of EAF steel be given by $a_{\text{pigiron,eaf}}$ and $a_{\text{scrap,eaf}}$, respectively. The mass balance implies

$$(1 + \varepsilon)(a_{\text{pigiron,eaf}} + a_{\text{scrap,eaf}}) = 1 \tag{5}$$

Since $a_{\text{pigiron,eaf}}$ refers to the amount of pig iron that is required to dilute a given amount of scrap $a_{\text{scrap,eaf}}$ with a dilution factor η, it follows from eq 3

$$a_{\text{pigiron,eaf}} = (\eta - 1)a_{\text{scrap,eaf}} \tag{6}$$

From eqs 5 and 6, it then follows

$$a_{\text{pigiron,eaf}} = \frac{\eta - 1}{(1 + \varepsilon)\eta}, \quad a_{\text{scrap,eaf}} = \frac{1}{(1 + \varepsilon)\eta} \tag{7}$$

Thus, the ratio of pig iron required for dilution to scrap in an EAF depends only on the factor of dilution η.

Analysis Methods

Goal and Scope. The goal of this analysis is to characterize the environmental implications of the ADF in the entire life cycle of EEE and investigate its effectiveness as a substitute for the current system, which does not apply the ADF. Because the same use phase applies to both the cases, the use phase is not considered. The application of the ADF itself is assumed to have no effect on the manufacturing (assembling) process of EEE. Further, in this study, we do no consider the recovery of any material (such as nonferrous metals and plastics) other than iron-based ones nor the generation of any loss or waste except WEEE. Due to the availability of data and its global implication, the environmental performance is represented in terms of the emission of CO_2 (this is in accord with a recent study on the recycling of stainless steel (*17*)).

Because of the limited data available on imported commodities, this study assumes, in accord with ref *18*, the same technology for the imported commodity and its domestically produced equivalent. The geographical scope of this study thus includes the countries exporting to Japan so far as their technologies can be represented by corresponding Japanese technologies. For mischmetal, however, this practice is not applicable because there is no domestic production in Japan: it is imported mainly from China. The energy requirements associated with the production (extraction and refinements) of mischmetal were taken from literature, while the energy requirements were assumed to be met by the Japanese technology.

Life-Cycle Calculations in Terms of CO_2. Our calculations of life-cycle environmental effects are based on the environmental extended input−output analysis (EEIO) (*12, 13, 14*), the general formula of which is given by

$$e = R(I - A)^{-1}f \tag{8}$$

where $A = [a_{ij}]$ refers to the technology matrix; $R = [r_j]$, the intervention matrix (the emission of CO_2 per activity); f, the final demand; and e, the CO_2 emission. Within the context of an LCA, the final demand corresponds to the functional unit. The major data source for A is the Japanese IO table for 2000 with 399 sectors (*19*) (hereafter referred to as the IOT), and for R, it is the NIES-3EID database (*20*).

The principal limitation of the existing IOT is the 399-sector disaggregation of the Japanese economy. For example, the steel sectors are not distinguished by steel types into carbon steel and special steel; however, production by BOF (basic oxygen furnace) and EAF process is distinguished. Waste management is divided into two sectors on institutional grounds (private or public), but there are no details of real EoL processes. Moreover, the IOT does not include details about mischmetal and hydrogen production. As shown below, detailed process information was used to compensate for these limitations, thus resulting in an extension of the original EEIO model.

Steel Sectors and the Flow of Scrap. Crude steel production was divided into four sectors by types of production processes (BOF and EAF) and by steel types (carbon steel and special steel including alloy steel) (see SI for details of data construction). Data limitations did not allow further disaggregation of special steel, say, into stainless steel and tool steel. It was assumed that the ADF-hydrogenation process separates the steel components of WEEE into carbon steel scrap and special steel scrap, while the degree of mixing, and hence η, is determined by the alloy content of stainless steel scrap, θ. The ratio of combination of pig iron to scrap in the EAF sector producing crude carbon steel was given by eq 7.

Production of EEE. As the sector in the IOT that corresponds to EEE, "household electric appliance excluding air conditioners" was chosen. While this sector contains a number of items ranging from refrigerators and washing machines to fans, vacuum cleaners, and rice cookers, refrigerators and washing machines constitute, with 34%, the largest product shares in monetary value. Henceforth, EEE refers to the combination of a unit of a representative refrigerator and a representative washing machine.

Because of the absence of a separate stainless steel sector, the steel mass of EEE, m, is divided into the mass of special steel (which includes stainless steel, m_α), m_s, and the mass of carbon steel, m_c; it should be understood that the denominator of eq 1 now reads $m = m_c + m_s$. Table 1 gives the representative composition of iron-based materials in refrigerators and washing machines, estimated on the basis of real samples (*2*). It is shown that $m = 61.7$ kg and $w_\alpha = 0.0648$. Using the WIO-MFA methodology (*21*), the original input coefficients for the EEE sector in the IOT were modified such that they yielded consistent results with the composition

TABLE 1. Composition of Iron-Based Materials in EEE[a]

steel type	refrigerator	washing machine	total	%
special steel: m_s	4.4	6.4	10.8	17.5
(stainless steel: m_α)	(0.6)	(3.4)	(4.0)	(6.48)
carbon steel: m_c	35.6	15.3	50.9	82.5
total steel: m	40.0	21.7	61.7	100

[a] Units: kg per unit. Special steel refers to alloyed steel and electromagnetic steel, while carbon steel refers to the remaining steel items. m_s contains m_α. Source: ref *2*.

TABLE 2. Scenarios[a]

scenario	ADF installed	disassembling method	special steel reclaimed as	carbon steel reclaimed as	dilution with pig iron in EAF
0C0	no	current		-	-
0C1	no	current		feed for EAF	yes
1C0	yes	current		-	
1H0	yes	ADF-hydrogenation		-	
1H2	yes	ADF-hydrogenation	crude special steel	feed for EAF	no
1H3	yes	ADF-hydrogenation	hot-rolled special steel	feed for EAF	no
1H4	yes	ADF-hydrogenation	hot-rolled special steel	crude carbon steel (40%), feed for EAF (60%)	no
1H5	yes	ADF-hydrogenation	hot-rolled special steel	crude carbon steel	-

[a] Current refers to the EoL process based on shredding. ADF-hydrogenation refers to the EoL process designed for the ADF where the ADF is activated by using hydrogen at 4 MPa and 373 K.

given in Table 1 (see SI for details). This modification resulted in the average (composite) EEE price per unit of 0.17 million Japanese yen, which is in accordance with actual values.

Production of Fasteners. For a unit of EEE, around 200 pieces of fasteners are used (an M4-sized fastener of length 10 mm and mass 1 g). Standard fasteners and the ADF are assumed to be manufactured by using the same technology and differ only in terms of their material compositions. The former consist of hot-rolled steel, while the latter consists of, besides steel, 10 at% (22 wt %) of mischmetal that can store 2.15 wt % of hydrogen. Compared to the steel mass of EEE, mischmetal occupies only a small composition, 0.07%.

The production (including material extraction) of mischmetal is characterized by the requirement of substantial amounts of energy (1377 MJ/kg; 40 times that of steel and 6 times that of aluminum) (*22*). Because no independent sector is available for mischmetal in the IOT, the environmental effect of its production was taken into account by incorporating its energy requirements into the production process of EEE.

EoL Processes. The EoL process consists of unpacking, initial disassembling, and a primary process (*23*). The current and ADF-hydrogenation processes differ in terms of their primary process. The data on the current shredding process were obtained from the JEMAI database (*24*). The data on the ADF-hydrogenation process (in particular, the input of electricity and hydrogen gas) were taken from ref *11*. The amount of hydrogen that is required to fill the volume of a unit of WEEE in the ADF-hydrogenation process was estimated to be 61.9 g (0.689 m^3). Assuming a heat capacity of 1.1 kJ/kg and an energy loss of 0.30, the amount of electricity (kWh) needed for the process was obtained. The amount of hydrogen that is actually absorbed by the ADFs is 4.73 g (0.0526 m^3). Under ideal conditions, wherein hydrogen gas can be recovered after each operation, the amount of hydrogen required for a unit of WEEE can be maintained at this level. In the following analysis, however, except where otherwise stated, a rather conservative stance is adopted, wherein 61.9 g of hydrogen is assumed to be used up per unit of WEEE.

Analogous to the incorporation of energy requirements of mischmetal production into EEE production, we incorporated the inputs associated with the production of hydrogen gas (the steam reforming process) (*24*) directly into the ADF-hydrogenation process including the additional emission of CO_2 that originates from the consumption of hydro carbons (naphtha) in the reforming process. Hydrogen gas is assumed to be supplied through a cylinder at a pressure of 4 MPa; no addition of pressure is needed in the ADF-hydrogenation process.

Functional Unit. The functional unit consists of the purchase of a unit of EEE, f_{EEE}, and its discard and submission to the EoL process, f_{WEEE}. The recycling of scrap in an EAF and the possible dilution of it with primary metals, however, call for additional considerations which are specific to our goal of analysis. Of the iron-based materials used in EEE, around only 10% originates from scrap (*21*); that is, EEE is mostly made of BOF steel. Accordingly, only a part of the scrap originating from WEEE can be used for the production of new EEE, while a major part of the scrap has to be put to other uses. Thus, a closed loop recycling of iron-based materials within the EEE sector is not possible. This implies the need for incorporating the demand for EAF steel as an additional element of the functional unit if the scrap is to be recycled in an EAF. Without incorporating the demand for EAF steel in the functional unit/final demand, the amount of EAF steel required for EEE will not be sufficient to absorb the scrap recovered in the EoL process.

The amount of EAF steel required for absorption, z, depends on the quality of scrap, eq 4. Neglecting, for the sake of simplicity, the small amount of scrap that is used in EEE production, the final demand for EAF steel, f_{EAF}, was set equal to z, eq 4. The amount of f_{EAF} will then differ between the two EoL processes because of its dependence on the quality of scrap.

To isolate the impact arising from dilution, the same level of f_{EAF} needs to be applied to both the EoL processes to ensure that the production of EAF remains at the same level. The two processes are associated with different ways of production in the EAF sector, eq 7. In the case of the current process, a certain amount of pig iron will be used to dilute the scrap, while in the ADF-hydrogenation process it is assumed that "clean scrap" equal to the amount of pig iron is supplied from other sources. Stated differently, a given level of f_{EAF} can be met by using scrap alone in the ADF case, while in the current case additional production of primary metals is required for dilution. The existence of surplus scrap is assumed for the purpose of isolating the effects of dilution in the EAF process.

Scenarios. The combination of fastener type (ADF or current), EoL treatment process (current or ADF-hydrogenation), use patterns of recovered scrap, and the need for dilution gives rise to a number of possible scenarios (Table 2). The scenarios are classified by a combination of two numbers and a letter between, with the first number referring to the use of ADF (0 indicating not used and 1 indicating used), the letter referring to the EoL process to which WEEE is subjected (C for current and H for ADF-hydrogenation), and the second number referring to the grade of use of the recovered scrap (0 for no recovery, 1 for feed for an EAF, and 2 or higher for more advanced use including reuse).

The scenario termed 0C1 in the third row of Table 2 refers to the current state of production and recycling, wherein no ADF is used in EEE, and iron-based materials are recovered by shredding and magnetic separation and recycled in an EAF to produce thin carbon steel sheet (grade 1) subject to dilution by pig iron. This will serve as a default scenario when issues of dilution are considered.

TABLE 3. Direct Effects of the Production of the ADF and the Operation of the ADF-Hydrogenation Process without Recovery and Disposal of Scrap under Various Scenarios (Table *2*; Given as % Relative to the Emission Level in 0C0)

scenario	description	10^3 kg-C	change in %
0C0	default	0.1315	
1C0	ADF production	0.1318	0.24
1H0	1C0 + ADF-hydrogenation process	0.1323	0.58
1H0 (a)	1H0 + increase in power consumption	0.1325	0.78
1H0 (b)	1H0 + reduced use of hydrogen	0.1321	0.43

TABLE 4. Effects of Upgrading the Use of Recovered Scrap Using ADF Relative to Its Use in EAF for Producing Thin Carbon Steel with No Need for Dilution

scenario	use of scrap (see Table *2* for details)	CO_2: 10^3 kg-C	Δ CO_2 (% relative to 1H2)
1H2	default: special steel scrap as crude special steel, carbon steel as feed for EAF	0.133	
1H3	reuse of special steel scrap as hot-rolled special steel	0.129	−2.5
1H4	reuse of 40% of carbon steel scrap	0.119	−10.5
1H5	reuse of entire carbon steel scrap	0.103	−22.4

The scenarios termed 1Hi with $i = 0,2,\cdots,5$ refer to cases where EEE is assembled with the ADF, subjected to the ADF-hydrogenation process when discarded, and the recovered scrap is used in different ways according to its quality. 1H3, 1H4, and 1H5 refer to the case of advanced reuse or recycling of scrap. The environmental effects associated with the production of the ADF can be assessed by comparing scenarios 0C0 and 1C0. Similarly, the environmental effects of the ADF-hydrogenation process can be assessed by comparing scenarios 1C0 and 1H0.

The effects of dilution are evaluated by comparing 1H2 with 0C1 for different values of η given by eq 2. From Figure 1 and Table 1 it follows that $\eta = 61 \times 0.0648 = 3.95$ when the "contaminant" is Cr in SUS 403, and $\eta = 5.50$ when it is Cr in SUS 430. For comparison, a hypothetical case wherein $\theta/\theta^* = 20$ was also considered; it gave $\eta = 1.29$.

Extension and Implementation. The extension of the EEIO model to incorporate the flow of WEEE and scrap and the EoL sector was facilitated in accordance with ref *15* by augmenting matrix A by two columns and rows, corresponding to the EoL sector and scrap (this results in a waste input−output model (WIO), see SI for details). The analysis was carried out by calculating eq 8 for different sets of A, R, and f, incorporating alternative scenarios (Table 2). For instance, two coefficients vectors were introduced to represent the unit process of EEE manufacturing with and without the ADF. For the scenarios with 0 as the first number, the vector without the ADF was used as the corresponding column elements of A and R, while for scenarios with 1 as the first number, the vector with the ADF was used. The EoL process was implemented in a similar fashion. The combination of scrap and pig iron in the EAF process is given by eq 7 for given η. Finally, the three elements of f are given by

$$f_{EEE} = P_{EEE} = 0.17, \quad (10^6 \text{ Japanese yen}) \qquad (9)$$

$$f_{EAF} = \begin{cases} 0, & \text{for the scenarios with 0 as the second number} \\ m\eta(1+\varepsilon) = 0.0617 \times \eta \times 1.008, & (10^3\text{kg}) \\ & \text{for the scenarios with the second number} \geq 1 \end{cases} \qquad (10)$$

$$f_{WEEE} = 1, \quad (\text{unit}) \qquad (11)$$

where P_{EEE} refers to the unit price of EEE, m is from Table 1, and ε is from ref *25*. The existence of mixed units reflects the hybrid nature of the model.

Results and Discussion

Direct Effects. Table 3 shows the effects of the introduction of ADF without any consideration of the use of recovered scrap (1C0 and 1H0 against 0C0). The increase in emission due to the introduction of ADF and the ADF-hydrogenation process is small, i.e., below 1% even under a fairly conservative estimation about energy requirements, 1H0(a). Optimistically, with regard to the recovery of hydrogen, 1H0(b), the increase can be kept well below 0.5%. The fact that the increase in emission can be maintained at this low level, notwithstanding the large energy requirements for producing mischmetal, can be attributed to its small mass in EEE (0.07%).

Effects of Dilution. Figure 4 compares the results of scenarios 0C1 and 1H2 (Table 2) for different values of η, with the final demand for EAF kept at the same level between the scenarios. The bars at the far left in Figure 4 refer to the case where no dilution is required ($\eta = 1.0$) in the current process. In this case, the ADF-hydrogenation process is only marginally superior to the current process. An increase in the dilution requirement results in a significant increase in the difference. The difference amounts to around 60% for $\eta = 3.95$ (the dilution factor for SUS 403 stainless steel scrap), and 86% for $\eta = 5.5$ (the dilution factor for SUS 430 stainless steel scrap). SI (Figure S3) provides the major effects on the level of sectoral production.

We now consider the case wherein the demand for EAF reflects the amount that is actually needed to absorb the

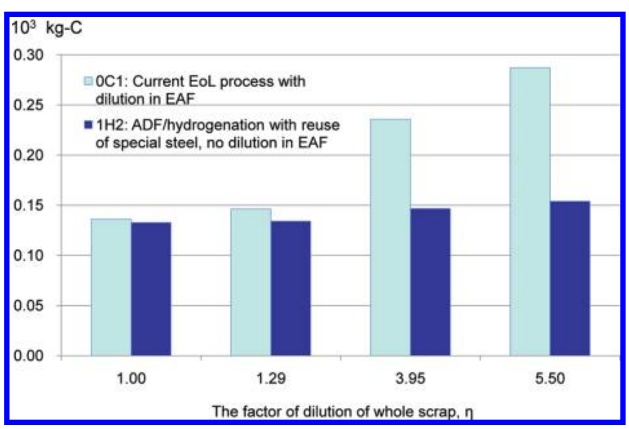

FIGURE 4. CO_2 emission from alternative treatment and recycling patterns for different dilution factors and given level of final demand. The numbers on the horizontal axis indicate the factor of dilution, η, for the whole scrap.

scrap recovered from WEEE. For scenario 1H2, the level of emission then remains at the level indicated by the dark bar at the far left in Figure 4, while for 0C1, it is subject to the dilution requirement. It follows that for $\eta = 5.5$, the difference in emission level increases to around 120%.

Effects of Upgrading and Reusing Scrap. Table 4 shows a comparison between the emission levels associated with the alternative use of scrap as a substitute for goods with different degrees of fabrication, for the case when no dilution is required. Advanced reuse of special steel scrap can reduce the emission by 2.5%. It is, however, the reuse of carbon steel scrap as crude carbon steel that can significantly reduce the emission. If 100% of carbon steel scrap could be used in this manner, the emission could be reduced by more than 20% compared to the current process. In the case where dilution is required, the ADF-hydrogenation process would achieve even greater superiority over the current system.

Economy-Wide Implications. The expected effect of applying the ADF on the reduction of CO_2 emission in Japan as a whole is briefly discussed. Around 25 Mkg of ferritic stainless scrap of WEEE origin is expected to be generated each year in Japan over the next decade (*3*). According to ref *17*, the separate recovery of this scrap can reduce CO_2 emission by up to 22 C-Mkg, which accounts for around 40% of the emission from EEE in 2005 (*20*).

Our analysis is concerned with CO_2 emission. Another important aspect related to the dissipation of scarce metal is total materials requirement (TMR); it addresses environmental effects associated with hidden materials flow such as the overburden and rock required to produce target materials (*2, 26*).

The declining population in Japan is expected to result in a reduction in the future demand for EAF steel, owing to the associated decline in construction (*27*). At the same time, the increasing and aging in-use stock of machinery and equipment will result in an increasing proportion of special steel in secondary metal stocks, and, consequently, a possible contamination of these stocks (*28*). If this trend continues further, it will become increasingly difficult to deal with the increasing contamination of scrap by dilution alone.

At the global level, the increasing quantity of the in-use stock reservoir of metals implies that more metals will have to be sourced from discarded in-use stock through recycling (*29*). With regard to quantitative availability, it is estimated that a sufficient amount of scrap will be available to balance the global requirement for iron (*30*). Therefore, the prevention of contamination of available scrap through mixing is of vital importance to ensure that their resource value is secured. This is the first LCA study ever conducted for the ADF under consideration of dilution effects. It is hoped that this study will encourage EEE manufacturers to seriously consider the possibility of using this new DfD technology.

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Supporting Information Available

Further detailed information on Figure 1, the ADF, the ADF-hydrogenation process, the modeling, the data, and computation results. This material is available free of charge via the Internet at http://pubs.acs.org.

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