1. Introduction

Rapid economic growth of the BRIC countries has resulted in an increase in the demand for iron and steel products. The annual worldwide production of crude steel is approximately 2 billion tons. There has been a corresponding increase in the production of crude steel in Japan. As a result, the significance of Japan as a source of iron and steel scraps has also increased. Scrap recycling, however, is subject to some problems, such as unstable supply conditions and contamination by impurities. A significant part of these problems can be attributed to the increasing use of electric devices, such as circuit boards, motors, and wiring harnesses, in high-tech products. These electric devices/equipments contain many kinds of metals, such as copper, lead, and zinc, which can become a source of contamination of steel scrap recovered from end-of-life vehicles (ELVs) or home appliances.

Here the contamination of tramp elements was analyzed using a Waste Input Output model, considering the following points: (1) the amount of ferrous scrap usage in iron and steel production process, (2) copper elimination from ELV scraps, and (3) contamination of copper in iron and steel products.

The results of scenario analysis indicated that copper contamination in crude steel production associated with the use of scrap from ELVs could be reduced by 2% by the use of a more recycle-oriented ELV treatment. The effects of copper elimination on CO₂ emission were more significant for ordinary steel production than special steel production.

KEY WORDS: waste input-output analysis; iron and steel material cycle; tramp element; carbon dioxide emission.
account the flow of waste and the activity of waste management.\textsuperscript{13}

The WIO provides an input–output methodology to consider the whole lifecycle of a product represented by production, use, and end-of-life, whereas the conventional IOA could not be used to deal with the last phase (albeit in an ad-hoc fashion). In the WIO model, the extended parts referring to waste flow and waste management are measured in physical units, and are consistent with the mass balance condition. For each type of waste, the amount of net generation (generation minus recycling) is equal to the amount of treatment it has undergone.

In this study, we aimed to assess the effects of alternative ELV treatment processes on copper contamination and CO\textsubscript{2} emission by using WIO analysis. For this purpose, the existing WIO database was substantially extended to be able to take proper account of the use of primary and secondary materials in the steel production process.

2. Development of WIO Table for Iron and Steel Material Cycle Analysis

2.1. Database Setting

Our starting point is the WIO table for Japan in 2000.\textsuperscript{14} In order to take proper account of the fact that acceptable amounts of ferrous scrap differ among different iron and steel products, the iron and steel sectors are further divided into 16 sectors (Table 1). While the existing WIO database considers the use of ion scrap in steel production process, its resolution is rather low when considering issues such as the accumulation of tramp elements associated with recycling. In particular, it does not consider the difference in the use pattern of scrap between ordinary steel and special steel, and between basic oxygen furnace (BOF) and electric arc furnace (EAF). Furthermore, iron and steel scrap are distinguished by the level of impurities.

2.2. Data Settings: Industrial Sectors

In the Japanese Input Output table, iron and steel production is divided into 16 sectors: BOF crude steel, EAF crude steel, ordinary section steel, ordinary sheet steel, ordinary steel strip, ordinary bar steel, other ordinary hot-rolled steel, special hot-rolled steel, steel pipe, cold-finished steel, coated steel, cast and forged steel, cast pipe, steel castings and forgings, shirring, and other steel products (Table 1). For this study, the crude steel sector and steel pipe sector were further divided into ordinary and special steel sectors, and hot-rolled steel is further divided into five types with reference to the amount of crude steel production by the furnace type and company.\textsuperscript{15} These procedures made it possible to consider the difference in the energy and material inputs required for producing each steel material. Table 2 shows the amount of input of pig iron, ferroalloy, and scrap that are required to produce crude steel worth one million yen. It is found that while only a small amount of steel scrap was used in BOF crude steel production, significant amounts of scrap were used in EAF ordinary (36.7 tons) and special crude steel production (13.8 tons). Disaggregation of crude steel by steel types, thus, enables us to explicitly take into account the difference in the use of scrap between ordinary steel and special steel. Table 3 gives the inputs that are required in the production of hot-rolled steel. EAF crude steel is mainly used in steel bar production, whereas only a limited amount of it is used in the production of steel sheet and steel strip. It follows that the impurities associated with steel scrap used in an EAF are likely to accumulate in steel bar and section steel.

2.3. Data Settings: Iron and Steel Scraps

Iron and steel scrap was distinguished according to market classification into 6 types\textsuperscript{2}: “Shindachi scrap”, “heavy scrap”, “shredded scrap”, “pressed scrap”, “other scrap”, and “return scrap”. “Shindachi scrap” is a kind of industrial scrap that is generated when steel sheets are punched-out. “Heavy scrap” mainly originates from construction debris, and a smaller portion of it originates from the production process of “section steel (ordinary steel)” and “steel bar

| Table 2. Ferrous material inputs per crude steel production. |
|---|
| | Unit | Crude steel (BOF) | Crude steel (EAF) |
| | Ordinary steel | Special steel | Ordinary steel | Special steel |
| Pig iron | Million yen | 0.057 | 0.337 | 0.020 | 0.017 |
| Ferro Alloy | Million yen | 0.054 | 0.057 | 0.039 | 0.272 |
| Iron and steel | scrap ton | 2.894 | 0.925 | 36.734 | 13.777 |

| Table 3. Crude steel inputs for production of steel products. |
|---|
| | Crude steel (converters) | Crude steel (electric furnaces) |
| | Ordinary steel | Special steel | Ordinary steel | Special steel |
| | Million yen | Million yen | Million yen | Million yen |
| Crude steel | 0.22 | 0.64 | 0.65 | 0.02 |
| | 0 | 0 | 0 | 0 |
| Crude steel | 0.45 | 0.04 | 0.02 | 0.65 |
| | 0 | 0 | 0 | 0 |
| Other hot-rolled | 0.40 | 0.0015 | 0 |
| | 0.46 | 0 |
| Steel pipes and tubes | 0.27 | 0.0008 | 0 |
| | 0.21 | 0 |
| Special steel | Million yen | Million yen | Million yen | Million yen |
| Crude steel | 0.40 | 0.0015 | 0 |
| | 0.46 | 0 |
| Special steel | Million yen | Million yen | Million yen | Million yen |
| Crude steel | 0.27 | 0.0008 | 0 |
| | 0.21 | 0 |
(ordinary steel)” as process waste. “Shredded scrap” and “pressed scrap” originate from waste treatment sectors, and “return scrap” originates from the production process of iron and steel industry as process waste. Scrap that originates from production processes is mostly recycled internally, with a recycling rate of close to 100%, because of its known composition. Note that “shredded scrap” and “pressed scrap” were assumed to be consumed in the EAF steel production process, with the allocation to ordinary EAF steel and special EAF steel being done in proportion to the production amount. The other scrap was allocated in proportion to the scrap demand of BOF and EAF steel production processes.

2.4. Coefficients of CO$_2$ Emission

The coefficients of CO$_2$ emission corresponding to the abovementioned division of steel sectors was also estimated for each steel production sector, the details of which are shown below.

The major data source for the CO$_2$ emission coefficients of industrial sectors is the 3EID database for 2000.\textsuperscript{16,17} \textbf{Table 4} shows the excerpt of CO$_2$ emission for pig iron, BOF crude steel, and EAF crude steel taken from the 3EID. The emission coefficient takes a negative value for BOF crude steel sector, which follows from the fact that it does not taken into account the carbon contents of pig iron as a material of crude steel. Pig iron contains approximately 5% carbon, which comes from coke added in the iron ore smelting process. In 3EID, it is assumed that the entire carbon content in pig iron is released in the pig iron production sector, whereas in reality, the carbon contained in pig iron remains in molten steel and is released in the crude steel production process.

Considering these points, the amounts of CO$_2$ emission in steel production have been modified taking into account the material balance in pig iron, BOF crude steel, and EAF crude steel (\textbf{Tables 5, 6, 7}). Pig iron, limestone, coke, and 12 types of fossil fuels and gasses are considered as sources of CO$_2$ emission. The re-calculated results shown in \textbf{Tables 8, 9, and 10} indicate that the carbon emission is mainly caused by pig iron and limestone in BOF crude steel, whereas it is due to limestone and steel scrap in EAF crude steel production. Coke and blast furnace gases emerge as the main carbon sources in the pig iron production sector, whereas pig iron is the main source of carbon in the BOF crude steel production sector.

The estimated results are summarized in \textbf{Table 11}. Figures 1 and 2 show the CO$_2$ emission associated with the production of one ton of steel before and after the disaggregation of steel sectors. Comparing the CO$_2$ emission associated with one ton of crude steel production, it is found that the emission from special steel is 1.07 times as large as that of ordinary steel for BOF and is 3.50 times as large as that of ordinary steel for EAF. It is also found that the emission associated with shaped steel and bar steel is 0.42 and 0.19 times, respectively, higher than that of steel sheet made of

\begin{table}[h]
\centering
\caption{CO$_2$ emission (unit: 10$^3$ t-C)}
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Pig iron} & \textbf{Crude steel} & & \\
 & Basic oxygen furnace & Electric arc furnace & \\
 & Ordinary steel & Special steel & Ordinary steel & Special steel & \\
\hline
CO$_2$ emissions & 35,100 & -486 & -164 & 1,230 & 877 & \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Inventory in pig iron sector.}
\begin{tabular}{|c|c|c|}
\hline
 & Unit & Input & Output \\
\hline
Limestone & ton & 17,753,143 & 0 \\
Bluff furnace slag & ton & 0 & 23,498 \\
Material coal & ton & 2,871,330 & 0 \\
Fuel coal & ton & 9,562,204 & 0 \\
Natural gas & 1000m$^3$ & 0 & 0 \\
Paraffin oil & kl & 75 & 0 \\
Bunker A & kl & 1,507 & 0 \\
Bunker B & 33,958 & 0 \\
Liquefied petroleum gas & ton & 8,259 & 0 \\
Hydrocarbon oil & ton & 0 & 0 \\
Petroleum coke & ton & 601,745 & 0 \\
Coke & ton & 35,960,569 & 0 \\
Coke-oven gas & 1000m$^3$ & 1,743,325 & 0 \\
Bluff furnace gas & 1000m$^3$ & 31,714,895 & 132,380,518 \\
Converter gas & 1000m$^3$ & 1,127,189 & 0 \\
Electric arc furnace gas & 1000m$^3$ & 0 & 0 \\
Coal tar & ton & 44,831 & 0 \\
Pig iron & ton & 0 & 81,070,748 \\
Iron scrap & ton & 2,488 & 0 \\
Steel scrap & ton & - & 0 \\
Utility gas & 1000m$^3$ & 2,904 & 0 \\
Blast furnace dust & ton & 0 & 1,216,015 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Inventory in BOF crude steel sector.}
\begin{tabular}{|c|c|c|}
\hline
 & Unit & Input & Output \\
\hline
Limestone & ton & 17,794,346 & 0 \\
Converter slag & ton & 0 & 10,640 \\
Fuel coal & ton & 694,609 & 0 \\
Natural gas & 1000m$^3$ & 0 & 0 \\
Paraffin oil & kl & 9,711 & 0 \\
Bunker A & kl & 18,488 & 0 \\
Bunker B & 2,473 & 0 \\
Liquefied petroleum gas & ton & 851 & 0 \\
Petroleum coke & ton & 0 & 0 \\
Coke & ton & 96,054 & 0 \\
Coke-oven gas & 1000m$^3$ & 334,090 & 0 \\
Blast furnace gas & 1000m$^3$ & 8,981 & 0 \\
Converter gas & 1000m$^3$ & 19,857 & 8,437,440 \\
Electric arc furnace gas & 1000m$^3$ & 0 & 0 \\
Coal tar & ton & 0 & 0 \\
Pig iron & ton & 77,145,345 & 0 \\
Crude steel(BOF) & ton & 0 & 75,784,436 \\
Iron scrap & ton & 557,251 & 0 \\
Steel scrap & ton & 6,274,734 & 0 \\
Utility gas & 1000m$^3$ & 15,421 & 0 \\
\hline
\end{tabular}
\end{table}
ordinary hot-rolled steel products, and the emission associated with special steel pipe is 1.82 times higher than that associated with steel pipe made of ordinary steel. By comparison, CO₂ emission from BOF and EAF ordinary steel production were 0.48 t-C and 0.12 t-C, respectively, according to the JEMAI database. Because of the different boundary conditions, it is not easily comparable, but it was confirmed that our estimated value was not different from that in the JEMAI database.

### Table 7. Inventory in EAF crude steel sector.

| Material          | Unit  | Input     | Output |
|-------------------|-------|-----------|--------|
| Limestone         | ton   | 1,003,835 | 0      |
| Converter slag    | ton   | 0         | 3,467  |
| Fuel coal         | ton   | 63,986    | 0      |
| Natural gas       | 1000m³| 1,524     | 0      |
| Paraffin oil      | kl    | 9.002     | 0      |
| Bunker A          | kl    | 10.466    | 0      |
| Bunker B · C      | kl    | 2.002     | 0      |
| Liquefied petroleum gas |  | 1,048 | 0 |
| Petroleum coke    | ton   | 6,668     | 0      |
| Coke              | ton   | 74,084    | 0      |
| Coke-oven gas     | 1000m³| 27,534    | 0      |
| Blast furnace gas | 1000m³| 689       | 0      |
| Converter gas     | 1000m³| 2,630     | 0      |
| Electric arc furnace gas | 1000m³| 0 | 98,148 |
| Coal tar          | ton   | 0         | 0      |
| Pig iron          | ton   | 1,780,351 | 0      |
| Crude steel(EAF)  | ton   | 0         | 30,660,032 |
| Iron scrap        | ton   | 742,014   | 0      |
| Steel scrap       | ton   | 30,628,884 | 0     |
| Utility gas       | 1000m³| 21,363    | 0      |

### Table 8. Carbon balance table in Pig iron sector (t-C).

| Material                      | Input     | Output |
|-------------------------------|-----------|--------|
| Limestone                     | 2,130,377 | 0      |
| Blast furnace slag            | 0         | 0      |
| Material coal                 | 2,160,389 | 0      |
| Fuel coal                     | 6,007,881 | 0      |
| Natural gas                   | 0         | 0      |
| Paraffin oil                  | 52        | 0      |
| Bunker A                      | 1,109     | 0      |
| Bunker B · C                  | 27,222    | 0      |
| Liquefied petroleum gas       | 6,772     | 0      |
| Hydrocarbon oil               | 0         | 0      |
| Petroleum coke                | 542,786   | 0      |
| Coke                          | 31,846,680| 0      |
| Coke-oven gas                 | 460,417   | 0      |
| Blast furnace gas             | 6,302,384 | 0      |
| Converter gas                 | 471,636   | 26,306,657 |
| Electric arc furnace gas      | 0         | 0      |
| Coal tar                      | 40,483    | 0      |
| Pig iron                      | 0         | 3,242,830 |
| Iron scrap                    | 100       | 0      |
| Steel scrap                   | 0         | 0      |
| Utility gas                   | 1,674     | 0      |
| Blast furnace dust            | 0         | 364,865 |
| Sum                           | 49,969,982| 29,914,291 |
| CO₂                           | 0         | 0      |
|                           | 20,655,691 |

### Table 9. Carbon balance table in BOF crude steel sector (t-C).

| Material                      | Input     | Output |
|-------------------------------|-----------|--------|
| Limestone                     | 2,135,322 | 0      |
| Converter slag                | 0         | 0      |
| Fuel coal                     | 436,868   | 0      |
| Natural gas                   | 0         | 0      |
| Paraffin oil                  | 6,696     | 0      |
| Bunker A                      | 13,662    | 0      |
| Bunker B · C                  | 1,982     | 0      |
| Liquefied petroleum gas       | 698       | 0      |
| Petroleum coke                | 0         | 0      |
| Coke                          | 85,065    | 0      |
| Coke-oven gas                 | 82,485    | 0      |
| Blast furnace gas             | 1,785     | 0      |
| Converter gas                 | 8,309     | 3,530,381 |
| Electric arc furnace gas      | 0         | 0      |
| Coal tar                      | 0         | 0      |
| Pig iron                      | 3,085,814 | 0      |
| Crude steel(BOF)              | 0         | 227,353 |
| Iron scrap                    | 22,290    | 0      |
| Steel scrap                   | 18,824    | 0      |
| Utility gas                   | 8,998     | 0      |
| Sum                           | 5,908,478 | 3,757,724 |
| CO₂                           | 0         | 0      |
|                           | 2,156,744 |

### Table 10. Carbon balance table in EAF crude steel sector (t-C).

| Material                      | Input     | Output |
|-------------------------------|-----------|--------|
| Limestone                     | 120,400   | 0      |
| Converter slag                | 0         | 0      |
| Fuel coal                     | 40,202    | 0      |
| Natural gas                   | 842       | 0      |
| Paraffin oil                  | 6,208     | 0      |
| Bunker A                      | 7,700     | 0      |
| Bunker B · C                  | 1,605     | 0      |
| Liquefied petroleum gas       | 859       | 0      |
| Petroleum coke                | 6,015     | 0      |
| Coke                          | 65,609    | 0      |
| Coke-oven gas                 | 6,798     | 0      |
| Blast furnace gas             | 135       | 0      |
| Converter gas                 | 1,100     | 0      |
| Electric arc furnace gas      | 0         | 41,067 |
| Coal tar                      | 0         | 0      |
| Pig iron                      | 71,214    | 0      |
| Crude steel(EAF)              | 0         | 91,980 |
| Iron scrap                    | 29,681    | 0      |
| Steel scrap                   | 90,086    | 0      |
| Utility gas                   | 12,465    | 0      |
| Sum                           | 460,979   | 133,047 |
| CO₂                           | 0         | 0      |
|                           | 927,982 |

### 3. The WIO Model

The WIO model is an analytical tool for life cycle analysis (LCA) that takes proper account of waste generation and recycling in physical terms. Its framework is given by

\[
\begin{bmatrix}
X_1 \\
X_2
\end{bmatrix}
= \begin{bmatrix}
A_{11} & A_{12} \\
SA_{12} & SA_{22}
\end{bmatrix}
\begin{bmatrix}
X_1 \\
X_2
\end{bmatrix}
+ \begin{bmatrix}
F_1 \\
F_2
\end{bmatrix}
\]

where \(X\) refers to production, \(A\) refers to the matrix of tech-
technical coefficients, and \( F \) is final demand. The subscript “1” and “2” attached to them refer to production sector and waste generation/recycling sectors, respectively. The waste allocation matrix \( S = [s_{ij}] \) represents the share of waste \( j \) treated by waste treatment \( i \).

Here, we deal with the implications of the contamination of iron and steel scrap by tramp elements for sustainable use of steel materials (including secondary materials). Special attention is paid to (1) the amount of iron and steel scrap and its utilization; (2) the elimination of copper from ferrous scraps; and (3) the contamination of iron and steel products by copper.

### 4. Analysis

#### 4.1. Scenarios

The following two scenarios were considered: (1) business as usual (BAU) and (2) recycle-oriented ELV treatment. Under the conventional ELV treatment, which corresponds to the BAU scenario, ELVs are pressed and shredded after the removal of parts such as engines, wheels, and electric wiring harnesses by using machine tools. The remaining copper content that is associated, among others, with small motors or harnesses is restricted to levels below 0.3% according to the requirements of EAF products. In the recycle-oriented ELV treatment scenario, the copper content in scrap is kept below 0.1%; this is made possible by manual disassembling of ELVs. A labor-intensive disassembly system is expensive, but it prevents the mixing of scrap with impurities.

Furthermore, the following are assumed in both scenarios:

1. The contamination of scrap originates from ELV only.
2. The copper content of scrap used in crude steel production (BOF/EAF) is retained in the steel products.

#### 4.2. Settings

Write \( c_i \) for the amount of copper contained in one ton of waste \( i \), and \( W_{ij} \) is the amount of waste material \( i \) that is utilized in the production sector \( j \), then the amount of copper present in waste materials utilized in the production sector \( j \), \( C_j \) is given by \( \sum c_i W_{ij} \). Under BAU and recycle-oriented scenarios, \( c_i \) was set at 0.003 and 0.001, respectively.

When the EAF crude steel production process uses the ELV scrap that is recovered under the BAU recycling system, 0.3% of the copper contained in the scraps is assumed to accumulate in the steel products. The copper input into the production sector \( j \), \( C_j \), then refers to the amount of copper contamination in crude steel.

#### 4.3. Results and Discussion

##### 4.3.1. CO\(_2\) Emissions and Copper Contamination

Table 11 shows the results from submitting one ton of ELV to each of the treatment processes based on the interviewed data. Under these settings, CO\(_2\) emission and copper contamination in crude steels were estimated. The results are summarized in Figs. 3 and 4. It was found that under conventional ELV treatment, the magnitude of copper contamination in crude steel production was about 2% higher than that in the recycle-oriented ELV treatment, with a 4732 t-C increase in CO\(_2\) emission in Japan. The copper-elimination effect was more significant in the production of ordinary steel than in the production of special steel; this finding is attributed to the fact that the production of ordinary steel uses larger amounts of press scrap than the production of special steel. The magnitude of copper contamination might appear smaller than is expected from the magnitude of copper content in ELV related scraps. This is mainly because pressed scrap accounted for 1.5% of the total scrap input in ELV special steel production.

##### 4.3.2. Policy Implications

Ordinary EAF crude steel production plays an important role in the recycling of ELV scrap. In other words, the demand for EAF steel is vital for the domestic recycling of iron and steel scrap originating from ELVs. EAF steel is mainly used for construction and civil engineering projects; EAF can utilize ELV scrap as long as there is enough demand in these sectors. The saturation of domestic construction demand in Japan, however, is expected to impose limi-
tation on the possibility of recycling low-grade scrap contaminated with impurities. It follows that the realization of sustainable steel material cycles calls for a shift from the conventional ELV treatment processes to recycle-oriented ones. Currently, recycle-oriented ELV treatment processes are labor intensive and expensive. Reduction in the size of scrap is expected to be useful to avoid the contamination of iron and steel scrap with copper, which originates from the mixing of wiring harnesses and motors with the ELVs. However, fine meshed shredding would require additional energy inputs and costs for its operation. Furthermore, the current situation is that the high-quality scraps recovered from recycle-oriented ELV treatment processes are not properly evaluated in scrap markets; their price does not significantly differ from the scrap of inferior quality obtained from conventional processes. From this, it is important to give the incentive pricing to treat ELV scrap with lower cost, for example, the recommendation of the smaller shredded scrap size or the higher purchasing price for scrap with lower copper contamination.

From the viewpoint of CO₂ emission, special steel production is associated with larger emission than ordinary steel production. Among the hot-rolled steel materials, the steel sheets, which are used in automobiles, accounts for the highest CO₂ emission among the ordinary steel materials. This is mainly caused by the difference in the intensity of energy use and the use of scrap. The fact indicates the need for the materials embodying high energy and CO₂, i.e., used automobiles, should be recovered with great care such that they can be reused with minimum loss in value instead of being used in a cascade manner.

### 5. Conclusion

In this study, the WIO table was set up focusing on the contamination of iron and steel scrap with impurities through the iron and steel manufacture process and estimated CO₂ emission of various steel material production sectors. Our sector classification and the estimated CO₂ emission coefficients made it possible to distinguish between the scrap demand in ordinary steel and special steel production. It was shown that CO₂ emission was higher during the unit production of special steel than the production of ordinary steel and that CO₂ emission was lower during the production of bar steel and section steel than the production of sheet steel.

The results of scenario analysis indicated that under the conventional ELV treatment, the amount of copper contamination in crude steel production was 2% higher than that obtained under the recycle-friendly ELV treatment. The effects of copper elimination were more significant in ordinary steel production than in special steel production. The results suggested the strong need for shifting to the recycle-oriented ELV treatment to realize the sustainable iron and steel material cycle.

For further discussions, it will be necessary to make more detailed investigation of the steel contamination issue caused not only by copper but also by other elements used in steel alloys. Simultaneously, a suitable analytical model would be required to assess this issue. WIO-MFA model would be one of the best possible choices to treat them as our future direction.

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