Supporting Information for

Optimal Recycling of Steel Scrap and Alloying Elements: Input-Output based Linear Programming Method with Its Application to End-of-Life Vehicles in Japan

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1. Methodology

1.1 Derivation of the linear program

Based on the WIO-MFA table, we define sets, variables, and constants. When considering a vector, we use two alternative notations. An n-vector and its elements are explicitly expressed as $\mathbf{v} = (v_1, v_2, \dots, v_n)$. Defining the set of subscripts or indices $N = \{1,2, \dots, n\}$, the same vector is alternatively expressed as $\mathbf{v} = (v_i)_{i \in N}$, without explicitly stating the order of indices. We also generalize the second notation to one with a set of indices, which are not necessarily integers. The definition of the sets, variables, and constants are listed below:

Sets

D: The set of domestic commodities

M: The set of imported commodities

S: The set of scraps

$A \subset D$: The set of alloy-steel commodities

$D' \subset D$: The set of domestic commodities that are raw materials for alloy steel production.

$M' \subset M$: The set of imported commodities that are raw materials for alloy steel production.

E: The set of elements considered in this study (i.e., iron, manganese, chromium, nickel, and molybdenum)

K: The set of objective functions

Note that, $(D' \cup M' \cup S) \cap A = \emptyset$, i.e., an alloy-steel commodity is not a raw material for any alloy-steel commodities.

Variables

x_i: Domestic production of commodity i ($i \in D$)

y_i: Final demand (domestic and export) for commodity i ($i \in D$)

y_i: Exogenous net demand (demand minus supply) for scrap i ($i \in S$)

a_{ij}: Direct demand for domestic commodity i per unit production of commodity j ($i, j \in D$)

a_{ij}: Direct demand for imported commodity i per unit production of commodity j ($i \in M, j \in D$)

a_{ij}: Direct net demand for scrap i per unit production of commodity j ($i \in S, j \in D$)

The notation a_{ij} is usually used in input-output economics literature to represent constants. In this study, however, a_{ij} is variable when $(i, j) \in D' \cup M' \cup S \times A$; otherwise, it is constant. We do not attach any subscripts or superscripts to a_{ij} to distinguish domestically produced commodities and imported commodities.

Constants

r_{ej}: Element e content of alloy-steel commodity j ($e \in E, j \in A$)

c_{ei}: Element e content of raw-material commodity i ($e \in E, i \in D' \cup M' \cup S$)

f_{eij}: Yield ratio of element e in raw material i when used for producing alloy steel j ($e \in E, i \in D' \cup M' \cup S, j \in A$)

b_i^k: Intensity of commodity i in terms of objective function k ($i \in D' \cup M'$, $k \in K$)

x_i^o: The observed domestic production of commodity i ($i \in D'$)

y_i^o: The observed demand for imported commodity i ($i \in M'$)

Our optimization problem has three different groups of equality constraints. The first group is the supply-demand balance of domestically produced commodities formulated as

$$x_i = \sum_{j \in D} a_{ij} x_j + y_i \quad (i \in D) \tag{S1}$$

This equation corresponds to the basic equation of IO analysis: $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$ where $\mathbf{I}$ is an identity matrix and $\mathbf{A}$ is an input coefficient matrix.[1] The second group represents the supply-demand balance of scrap formulated as

$$\sum_{j \in D} a_{ij} x_j + y_i = 0 \;\; (i \in S) \tag{S2}$$

or equivalently,

$$\sum_{j \in D} a_{ij}^{\mathrm{s}} x_j + y_i^{\mathrm{s}} = \sum_{j \in D} a_{ij}^{\mathrm{d}} x_j + y_i^{\mathrm{d}} \;\; (i \in S), \tag{S3}$$

where the superscript s stands for the supply (generation) of scrap and d for demand for scrap, and the net demands are expressed as $a_{ij} = a_{ij}^{\mathrm{d}} - a_{ij}^{\mathrm{s}}$ and $y_i = y_i^{\mathrm{d}} - y_i^{\mathrm{s}}$. The third group of constraints refers to the mass balance of sectors that produce alloy steel, in terms of elements, and is defined as

$$r_{ej} x_j = \sum_{i \in D' \cup M' \cup S} f_{eij} c_{ei} a_{ij} x_j \;\; (e \in E, j \in A) \tag{S4}$$

We also set upper bounds on the amount of domestic productions and demand for imports of virgin AE sources as follows:

$$\begin{aligned} x_i &\le x_i^o \;\; (i \in D') \\ \sum_{j \in D} a_{ij} x_j &\le y_i^o \;\; (i \in M') \end{aligned} \tag{S5}$$

These inequality constraints rule out meaningless solutions which are unrealistically different from the observed values. Without the constraints, single virgin AE-supplying commodities for each AE, which have the lowest intensities on the objective functions, are consumed to achieve the objectives.

Then, the optimization problem to be solved can be expressed as:

$$
\left|\begin{array}{ll}
\text{minimize} & \sum_{v \in D' \cup M'} \sum_{j \in D} b_v^k a_{vj} x_j \\
\text{subject to} & x_i = \sum_{j \in D} a_{ij} x_j + y_i \ \ (i \in D) \\
& \sum_{j \in D} a_{ij} x_j + y_i = 0 \ \ (i \in S) \\
& r_{ej} x_j = \sum_{i \in D' \cup M' \cup S} f_{eij} c_{ei} a_{ij} x_j \ \ (e \in E, j \in A) \\
& \sum_{j \in D} a_{ij} x_j \leq y_i^o \ \ (i \in M') \\
& x_j \leq x_j^o \ \ (j \in D') \\
& a_{ij} \geq 0 \ \ (i \in D' \cup M' \cup S, j \in A) \\
& x_j \geq 0 \ \ (j \in D)
\end{array}\right. \qquad \text{(S6)}
$$

Note that some of a_{ij}s as well as $x_j s$ are decision variables in this optimization problem. More precisely, a_{ij} is a decision variable when $i \in D' \cup M' \cup S$, and $j \in A$, i.e., i is a raw material for alloy steel j; otherwise, a_{ij} is constant.

The factor $a_{ij} x_j$ on the right-hand side of (S4), i.e., the third equality constraint of (S6), makes the equation nonlinear. However, it can be linearized along the line of Kondo and Nakamura.[2] Introducing variables z_{ij} such that $z_{ij} = a_{ij} x_j$ $(i \in D' \cup M' \cup S, j \in A)$, we can rewrite (S6) as the following linear program:

$$
\left|\begin{array}{ll}
\text{minimize} & \sum_{v\in D'\cup M'}\sum_{j\in D\setminus A} b_v^k a_{vj}x_j + \sum_{v\in D'\cup M'}\sum_{j\in A} b_v^k z_{vj} \\
\text{subject to} & x_i = \sum_{j\in D} a_{ij}x_j + y_i \ \ (i \in D \setminus D') \\
& x_i = \sum_{j\in D\setminus A} a_{ij}x_j + \sum_{j\in A} z_{ij} + y_i \ \ (i \in D') \\
& \sum_{j\in D\setminus A} a_{ij}x_j + \sum_{j\in A} z_{ij} + y_i = 0 \ \ (i \in S) \\
& r_{ej}x_j = \sum_{i\in D'\cup M'\cup S} f_{eij}c_{ei}z_{ij} \ \ \ (e \in E, j \in A) \\
& \sum_{j\in D} a_{ij}x_j \le y_i^o \ \ (i \in M') \\
& x_j \le x_j^o \ \ (j \in D') \\
& z_{ij} \ge 0 \ \ (i \in D' \cup M' \cup S, j \in A) \\
& x_j \ge 0 \ \ (j \in D)
\end{array}\right. \tag{S7}
$$

1.2 Multi-objective optimization

We separately solved the two linear programs that share the common constraints and have different objective functions to minimize, i.e., economic cost and GHG emission. To jointly solve the two programs as a multi-objective optimization problem, we constructed a linear program which has an objective function equal to the weighted average of the two objective functions with varying weights. This program with infinitely many different weight values can be efficiently solved using parametric analysis.[3] However, we employed a brute force method, that is, we solved the program 101 times with weights $(0.00,1.00)$, $(0.01,0.99)$, …, $(0.99,0.01)$, and $(1.00,0.00)$.

2. Background data

2.1 Sets

2.1.1 A: Alloy-steel commodities

In the analysis, 8 grades of ordinary steel and 19 grades of special steel production in the EAF were included in the set of Alloy-steel commodities: A summarized in Table S1. The sector definitions were referred to our previous researches[4-6].

Table S1 List of the alloy-steel grade in the set A

Grade name
EAF-Ordinary section steel
EAF-Ordinary steel sheets and plates
EAF-Ordinary steel bar
EAF-Other hot-rolled ordinary steel
EAF-Ordinary steel pipe
EAF-Cold-finished ordinary steel
EAF-Coated steel
EAF-Other ordinary steel
EAF-Carbon tool steel
EAF-Alloy tool steel
EAF-High speed steel
EAF-Other tool steel
EAF-Structural carbon steel
EAF-Structural alloy steel
EAF-Spring steel
EAF-Bearing steel
EAF-Cr stainless steel
EAF-Cr-Ni stainless steel
EAF-Heat-resistant steel
EAF-Free-cutting steel
EAF-Piano wire rod
EAF-High-tensile steel
EAF-Weathering steel
EAF-Low-temp. steel
EAF-High-tensile steel pipe
EAF-Stainless steel pipe
EAF-Other special steel

2.1.2 D': Domestic commodities which are raw materials for production of alloy steel

Raw materials for production of alloy steel consists of 14 kinds of iron and alloying elements (AEs) sources as summarized in Table S2. They are roughly categorized into pig iron, ferroalloys, metal itself (e.g. ingot and powder), and other sources.[4 5, 7]

2.1.3 M': Imported commodities which are raw materials for production of alloy steel

Components of M' is consistent with D' as shown in Table S2.

Table S2 The list of raw materials in the set D' and M'

Set	Name
D'	Pig iron
D'	Ferromanganese
D'	Silicomanganese
D'	Ferrochromium
D'	Ferrosilicon
D'	Ferronickel
D'	Ferromolybdenum
D'	Other ferroalloys
D'	Metallic manganese
D'	Molybdenum oxide briquette
D'	Metallic Nickel
D'	Other Ni sources
D'	Other Cr sources
D'	Other Mn sources
M'	Pig iron (Imp)
M'	Ferromanganese (Imp)
M'	Silicomanganese (Imp)
M'	Ferrochromium (Imp)
M'	Ferrosilicon (Imp)
M'	Ferronickel (Imp)
M'	Ferromolybdenum (Imp)
M'	Other ferroalloys (Imp)
M'	Metallic manganese (Imp)
M'	Molybdenum oxide briquette (Imp)
M'	Metallic Nickel (Imp)
M'	Other Ni sources (Imp)
M'	Other Cr sources (Imp)
M'	Other Mn sources (Imp)

2.1.4 S: Scrap

In the set of scrap, roughly classifying three kinds of scrap are included; Other iron and steel scrap, Parts scrap, and Process scrap for EAF steelmaking. In our previous studies, steel scrap has provided some AEs for alloy-steel production. In this study, we assumed only Process scrap for EAF steelmaking derives AEs into EAF steelmaking in addition to parts scrap, and Other iron and steel scrap can be regarded as pure iron for the sake of simplicity of the model. Because alloy-steel in process scrap would be relatively easily distinguished by each other, a process scrap of an alloy-steel is consumed only in the same grade of alloy-steel production.

Table S3 The list of scrap included in the set *S*

Scrap name
Other iron and steel scrap
Parts scrap-Body
Parts scrap-Suspension
Parts scrap-Shaft
Parts scrap-Steering
Parts scrap-Interior
Parts scrap-Transmission
Parts scrap-Brake
Parts scrap-Exhaust
Scrap for EAF-Ordinary steel (General)
Scrap for EAF-Ordinary steel sheets and plates
Scrap for EAF-Other hot-rolled ordinary steel
Scrap for EAF-Ordinary steel pipe
Scrap for EAF-Other ordinary steel
Scrap for EAF-Carbon tool steel
Scrap for EAF-Alloy tool steel
Scrap for EAF-High speed steel
Scrap for EAF-Other tool steel
Scrap for EAF-Structural carbon steel
Scrap for EAF-Structural alloy steel
Scrap for EAF-Spring steel
Scrap for EAF-Bearing steel
Scrap for EAF-Cr stainless steel
Scrap for EAF-Cr-Ni stainless steel
Scrap for EAF-Heat-resistant steel
Scrap for EAF-Free-cutting steel
Scrap for EAF-Piano wire rod
Scrap for EAF-High-tensile steel
Scrap for EAF-Weathering steel
Scrap for EAF-Low-temp. steel
Scrap for EAF-High-tensile steel pipe
Scrap for EAF-Stainless steel pipe
Scrap for EAF-Other special steel

2.2 Constants

2.2.1 c_{ei}: Element e content of raw-material commodity i

In this study, five elements are taken into account. ($E = \{\mathrm{Fe}, \mathrm{Mn}, \mathrm{Cr}, \mathrm{Ni}, \mathrm{Mo}\}$). Element contents are summarized in Table S4 and S5 based on our previous studies[4, 5, 7].

Table S4 Element content of raw-material commodities ($i \in D' \cup M'$)

Set	$i \in D' \cup M'$	*e*				
		Fe	Mn	Cr	Ni	Mo
D'	Pig iron	0.998	0.003	0.000	0.000	0.000
D'	Ferromanganese	0.205	0.795	0.000	0.000	0.000
D'	Silicomanganese	0.000	0.610	0.000	0.000	0.000
D'	Ferrochromium	0.388	0.000	0.612	0.000	0.000
D'	Ferrosilicon	1.000	0.000	0.000	0.000	0.000
D'	Ferronickel	0.775	0.000	0.000	0.225	0.000
D'	Ferromolybdenum	0.400	0.000	0.000	0.000	0.600
D'	Other ferroalloys	1.000	0.000	0.000	0.000	0.000
D'	Metallic manganese	0.000	1.000	0.000	0.000	0.000
D'	Molybdenum oxide briquette	0.000	0.000	0.000	0.000	0.600
D'	Metallic Nickel	0.000	0.000	0.000	1.000	0.000
D'	Other Ni sources	0.000	0.000	0.000	0.524	0.000
D'	Other Cr sources	0.000	0.000	0.207	0.000	0.000
D'	Other Mn sources	0.699	0.301	0.000	0.000	0.000
M'	Pig iron (Imp)	0.998	0.003	0.000	0.000	0.000
M'	Ferromanganese (Imp)	0.205	0.795	0.000	0.000	0.000
M'	Silicomanganese (Imp)	0.000	0.610	0.000	0.000	0.000
M'	Ferrochromium (Imp)	0.427	0.000	0.573	0.000	0.000
M'	Ferrosilicon (Imp)	1.000	0.000	0.000	0.000	0.000
M'	Ferronickel (Imp)	0.775	0.000	0.000	0.225	0.000
M'	Ferromolybdenum (Imp)	0.400	0.000	0.000	0.000	0.600
M'	Other ferroalloys (Imp)	1.000	0.000	0.000	0.000	0.000
M'	Metallic manganese (Imp)	0.000	1.000	0.000	0.000	0.000
M'	Molybdenum oxide briquette (Imp)	0.000	0.000	0.000	0.000	0.600
M'	Metallic Nickel (Imp)	0.000	0.000	0.000	1.000	0.000
M'	Other Ni sources (Imp)	0.000	0.000	0.000	0.524	0.000
M'	Other Cr sources (Imp)	0.000	0.000	0.207	0.000	0.000
M'	Other Mn sources (Imp)	0.699	0.301	0.000	0.000	0.000

Table S5 Element content of scrap commodities ($i \in S$)

Set	$i \in S$	e				
		Fe	Mn	Cr	Ni	Mo
S	Other iron and steel scrap	1.000	0.000	0.000	0.000	0.000
S	Parts scrap-Body	0.985	0.005	0.002	0.001	0.000
S	Parts scrap-Suspension	0.989	0.007	0.002	0.001	0.000
S	Parts scrap-Shaft	0.985	0.004	0.007	0.002	0.000
S	Parts scrap-Steering	0.990	0.004	0.003	0.001	0.000
S	Parts scrap-Interior	0.991	0.005	0.001	0.001	0.000
S	Parts scrap-Transmission	0.988	0.004	0.005	0.002	0.000
S	Parts scrap-Brake	0.996	0.002	0.001	0.000	0.000
S	Parts scrap-Exhaust	0.867	0.005	0.101	0.024	0.002
S	Scrap for EAF-Ordinary steel (General)	0.964	0.036	0.000	0.000	0.000
S	Scrap for EAF-Ordinary steel sheets and plates	0.914	0.085	0.000	0.000	0.000
S	Scrap for EAF-Other hot-rolled ordinary steel	0.964	0.036	0.000	0.000	0.000
S	Scrap for EAF-Ordinary steel pipe	0.915	0.085	0.000	0.000	0.000
S	Scrap for EAF-Other ordinary steel	0.971	0.029	0.000	0.000	0.000
S	Scrap for EAF-Carbon tool steel	0.959	0.037	0.002	0.002	0.000
S	Scrap for EAF-Alloy tool steel	0.932	0.011	0.034	0.021	0.003
S	Scrap for EAF-High speed steel	0.955	0.008	0.038	0.000	0.000
S	Scrap for EAF-Other tool steel	1.000	0.000	0.000	0.000	0.000
S	Scrap for EAF-Structural carbon steel	0.969	0.031	0.000	0.000	0.000
S	Scrap for EAF-Structural alloy steel	0.945	0.027	0.014	0.014	0.000
S	Scrap for EAF-Spring steel	0.965	0.030	0.005	0.000	0.000
S	Scrap for EAF-Bearing steel	0.980	0.007	0.010	0.003	0.000
S	Scrap for EAF-Cr stainless steel	0.820	0.025	0.155	0.000	0.000
S	Scrap for EAF-Cr-Ni stainless steel	0.739	0.024	0.130	0.107	0.000
S	Scrap for EAF-Heat-resistant steel	0.882	0.026	0.084	0.007	0.001
S	Scrap for EAF-Free-cutting steel	0.975	0.025	0.000	0.000	0.000
S	Scrap for EAF-Piano wire rod	0.973	0.027	0.000	0.000	0.000
S	Scrap for EAF-High-tensile steel	0.954	0.046	0.000	0.000	0.000
S	Scrap for EAF-Weathering steel	0.948	0.046	0.005	0.002	0.000
S	Scrap for EAF-Low-temp. steel	0.954	0.046	0.000	0.000	0.000
S	Scrap for EAF-High-tensile steel pipe	0.954	0.046	0.000	0.000	0.000
S	Scrap for EAF-Stainless steel pipe	0.748	0.024	0.145	0.083	0.000
S	Scrap for EAF-Other special steel	0.939	0.022	0.026	0.013	0.000

2.2.2 r_{ej}: Element e content of alloy-steel commodity j

Contents of AEs in alloy-steel commodities were calculated based on the industrial standards and share of specific grades in the standard of 19 grades of alloy-steel in our previous study[4, 5] as shown in Table S6. In the analysis, the contents of AEs in alloy-steel commodities represent the requirement for AEs amount derived by raw-materials and scrap.

Table S6 Contents of AEs in alloy-steel commodities (i.e. element requirements)

	e				
$j \in A$	Fe	Mn	Cr	Ni	Mo
EAF-Ordinary section steel	0.993	0.003	0.000	0.000	0.000
EAF-Ordinary steel sheets and plates	0.988	0.008	0.000	0.000	0.000
EAF-Ordinary steel bar	0.993	0.003	0.000	0.000	0.000
EAF-Other hot-rolled ordinary steel	0.993	0.003	0.000	0.000	0.000
EAF-Ordinary steel pipe	0.988	0.008	0.000	0.000	0.000
EAF-Cold-finished ordinary steel	0.993	0.003	0.000	0.000	0.000
EAF-Coated steel	0.993	0.003	0.000	0.000	0.000
EAF-Other ordinary steel	0.993	0.003	0.000	0.000	0.000
EAF-Carbon tool steel	0.987	0.009	0.002	0.002	0.000
EAF-Alloy tool steel	0.927	0.002	0.036	0.019	0.014
EAF-High speed steel	0.957	0.002	0.040	0.000	0.000
EAF-Other tool steel	0.999	0.000	0.000	0.000	0.000
EAF-Structural carbon steel	0.991	0.007	0.000	0.000	0.000
EAF-Structural alloy steel	0.965	0.006	0.015	0.012	0.001
EAF-Spring steel	0.986	0.007	0.006	0.000	0.000
EAF-Bearing steel	0.984	0.002	0.010	0.002	0.000
EAF-Cr stainless steel	0.814	0.006	0.178	0.000	0.001
EAF-Cr-Ni stainless steel	0.730	0.006	0.156	0.105	0.002
EAF-Heat-resistant steel	0.887	0.006	0.093	0.006	0.006
EAF-Free-cutting steel	0.993	0.006	0.000	0.000	0.000
EAF-Piano wire rod	0.992	0.006	0.000	0.000	0.000
EAF-High-tensile steel	0.988	0.011	0.000	0.000	0.000
EAF-Weathering steel	0.981	0.011	0.005	0.002	0.000
EAF-Low-temp. steel	0.988	0.011	0.000	0.000	0.000
EAF-High-tensile steel pipe	0.988	0.011	0.000	0.000	0.000
EAF-Stainless steel pipe	0.738	0.006	0.173	0.081	0.002
EAF-Other special steel	0.951	0.005	0.029	0.012	0.001

2.2.3 f_{eij}: Yield ratio of element e in raw material i when used for producing alloy steel j

Certain portions of AEs and iron in raw-materials and scrap introduced to EAF steelmaking are lost as losses during the process. AEs are thermodynamically distributed to molten steel, steelmaking slag, and gas phases.[7] Accordingly, yield ratio of elements were applied to the calculation for the balance of elements in alloy-steel production as summarized in Table S7, S8 and S9. For AEs (i.e. Mn, Cr, Ni, Mo), yield ratios of the input of raw-materials and scrap to alloy steel production are varied by sources but generally common for all alloy-steel commodities. On the other hand, yield ratio of Fe from all sources are uniform for sources but varied by target alloy-steel. Yield ratios for $i \in D' \cup M'$ were generated based on the mass balance between inputs of AE sources and outputs of AEs contained in alloy steel in our previous studies[4-6] according to the data from various statistics.[8-10] It should be notable that yield ratio of Mo was set probably lower than that of thermodynamically estimated ratio (i.e. =1).[7] As Nakajima et al. noted,[11] molybdenum are introduced to ordinary steel production as well as special steel (i.e. alloy steel) production whereas molybdenum contents and requirements in ordinary steel are not defined in the industrial standard. Consequently, the input of molybdenum to steelmaking became larger than output because only molybdenum in special steel were considered but molybdenum contained in ordinary steel could not be counted. Therefore, the yield ratio of molybdenum becomes less than 1. In addition, yield ratios of molybdenum were different among molybdenum sources because of the same reason. Yield ratios for AE inputs from parts scrap were referred to Matsubae et al.[12] except for molybdenum.

Table S7 Yield ratios of AEs in raw-materials when used for alloy-steel production in EAF

		e			
Set	$i \in D' \cup M'$	Mn	Cr	Ni	Mo
D'	Pig iron	0.000	1.000	1.000	0.706
D'	Ferromanganese	0.741	1.000	1.000	0.706
D'	Silicomanganese	0.741	1.000	1.000	0.706
D'	Ferrochromium	0.741	1.000	1.000	0.706
D'	Ferrosilicon	0.741	1.000	1.000	0.706
D'	Ferronickel	0.741	1.000	1.000	0.706
D'	Ferromolybdenum	0.741	1.000	1.000	0.649
D'	Other ferroalloys	0.741	1.000	1.000	0.706
D'	Metallic manganese	0.741	1.000	1.000	0.706
D'	Molybdenum oxide briquette	0.741	1.000	1.000	0.750
D'	Metallic Nickel	0.741	1.000	1.000	0.706
D'	Other Ni sources	0.741	1.000	1.000	0.706
D'	Other Cr sources	0.741	1.000	1.000	0.706
D'	Other Mn sources	0.741	1.000	1.000	0.706
M'	Pig iron (Imp)	0.000	1.000	1.000	0.706
M'	Ferromanganese (Imp)	0.741	1.000	1.000	0.706
M'	Silicomanganese (Imp)	0.741	1.000	1.000	0.706
M'	Ferrochromium (Imp)	0.741	1.000	1.000	0.706
M'	Ferrosilicon (Imp)	0.741	1.000	1.000	0.706
M'	Ferronickel (Imp)	0.741	1.000	1.000	0.706
M'	Ferromolybdenum (Imp)	0.741	1.000	1.000	0.649
M'	Other ferroalloys (Imp)	0.741	1.000	1.000	0.706
M'	Metallic manganese (Imp)	0.741	1.000	1.000	0.706
M'	Molybdenum oxide briquette (Imp)	0.741	1.000	1.000	0.750
M'	Metallic Nickel (Imp)	0.741	1.000	1.000	0.706
M'	Other Ni sources (Imp)	0.741	1.000	1.000	0.706
M'	Other Cr sources (Imp)	0.741	1.000	1.000	0.706
M'	Other Mn sources (Imp)	0.741	1.000	1.000	0.706

Table S8 Yield ratios of AEs in scrap when used for alloy-steel production in EAF

Set	$i \in S$	e Mn	Cr	Ni	Mo
S	Other iron and steel scrap	0.730	0.890	1.000	1.000
S	Parts scrap-Body	0.730	0.890	1.000	0.735
S	Parts scrap-Suspension	0.730	0.890	1.000	0.735
S	Parts scrap-Shaft	0.730	0.890	1.000	0.735
S	Parts scrap-Steering	0.730	0.890	1.000	0.735
S	Parts scrap-Interior	0.730	0.890	1.000	0.735
S	Parts scrap-Transmission	0.730	0.890	1.000	0.735
S	Parts scrap-Brake	0.730	0.890	1.000	0.735
S	Parts scrap-Exhaust	0.730	0.890	1.000	0.735
S	Scrap for EAF-Ordinary steel (General)	0.146	0.702	1.000	1.000
S	Scrap for EAF-Ordinary steel sheets and plates	0.146	0.702	1.000	1.000
S	Scrap for EAF-Other hot-rolled ordinary steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Ordinary steel pipe	0.146	0.702	1.000	1.000
S	Scrap for EAF-Other ordinary steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Carbon tool steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Alloy tool steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-High speed steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Other tool steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Structural carbon steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Structural alloy steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Spring steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Bearing steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Cr stainless steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Cr-Ni stainless steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Heat-resistant steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Free-cutting steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Piano wire rod	0.146	0.702	1.000	1.000
S	Scrap for EAF-High-tensile steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Weathering steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-Low-temp. steel	0.146	0.702	1.000	1.000
S	Scrap for EAF-High-tensile steel pipe	0.146	0.702	1.000	1.000
S	Scrap for EAF-Stainless steel pipe	0.146	0.702	1.000	1.000
S	Scrap for EAF-Other special steel	0.146	0.702	1.000	1.000

Table S9 Yield ratio of iron input from various sources to steel production(Transposed) in EAF

$j \in A$	Fe
EAF-Ordinary section steel	0.971
EAF-Ordinary steel sheets and plates	0.974
EAF-Ordinary steel bar	0.971
EAF-Other hot-rolled ordinary steel	0.970
EAF-Ordinary steel pipe	0.974
EAF-Cold-finished ordinary steel	0.971
EAF-Coated steel	0.971
EAF-Other ordinary steel	0.959
EAF-Carbon tool steel	0.973
EAF-Alloy tool steel	0.899
EAF-High speed steel	0.934
EAF-Other tool steel	0.971
EAF-Structural carbon steel	0.975
EAF-Structural alloy steel	0.948
EAF-Spring steel	0.970
EAF-Bearing steel	0.960
EAF-Cr stainless steel	0.803
EAF-Cr-Ni stainless steel	0.722
EAF-Heat-resistant steel	0.871
EAF-Free-cutting steel	0.974
EAF-Piano wire rod	0.975
EAF-High-tensile steel	0.978
EAF-Weathering steel	0.971
EAF-Low-temp. steel	0.978
EAF-High-tensile steel pipe	0.978
EAF-Stainless steel pipe	0.730
EAF-Other special steel	0.923

2.2.4 b_i^k: Intensity of commodity i in terms of objective function k

The intensity of commodity i in terms of the objective function is embodied GHG emission intensity when the objective function is GHG emission, whereas the intensity is price when the objective function is cost (Table S10). For embodied GHG, LCI database IDEA ver. 1.0 [13] and Ecoinvent Life Cycle Inventory database v2.2 [14] were referred for domestically produced commodities and imported commodity, respectively. For unit price of commodities, we referred to an appendix for IO table for Japan 2005[15] for domestically produced commodities and the trade statistics[16] for imported commodities. In terms of price of commodities, there are less differences between domestically produced commodities and imported ones. On the other hand, there are large gap between them in terms of embodied GHG. Of course, this difference would be derived by the difference of the data sources developed reflecting regional conditions such as the energy mixes and production processes.

Table S10 Intensity of commodities in terms of each objective function

Set	$i \in D' \cup M'$	GHG t/t-CO_2eq	Cost 10^6JPY/t
D'	Pig iron	1.30	0.03
D'	Ferromanganese	6.70	0.10
D'	Silicomanganese	11.17	0.10
D'	Ferrochromium	9.32	0.22
D'	Ferrosilicon	0.00	0.00
D'	Ferronickel	2.72	0.34
D'	Ferromolybdenum	3.68	4.50
D'	Other ferroalloys	0.00	0.00
D'	Metallic manganese	5.70	0.17
D'	Molybdenum oxide briquette	1.12	4.00
D'	Metallic Nickel	14.59	1.67
D'	Other Ni sources	4.36	1.39
D'	Other Cr sources	4.80	0.11
D'	Other Mn sources	0.01	0.01
M'	Pig iron (Imp)	1.30	0.03
M'	Ferromanganese (Imp)	1.00	0.09
M'	Silicomanganese (Imp)	1.00	0.09
M'	Ferrochromium (Imp)	1.90	0.10
M'	Ferrosilicon (Imp)	0.00	0.00
M'	Ferronickel (Imp)	9.20	0.47
M'	Ferromolybdenum (Imp)	2.62	5.14
M'	Other ferroalloys (Imp)	0.00	0.00
M'	Metallic manganese (Imp)	2.60	0.17
M'	Molybdenum oxide briquette (Imp)	2.60	5.04
M'	Metallic Nickel (Imp)	10.90	1.67
M'	Other Ni sources (Imp)	4.36	1.39
M'	Other Cr sources (Imp)	4.80	0.11
M'	Other Mn sources (Imp)	0.01	0.01

3. Detailed results

3.1 Choice of virgin sources of AEs

The optimal choices of virgin AE sources can be basically interpreted by observing their prices and embodied GHG emission intensities. As mentioned in the main text, the demand for AE virgin sources with higher prices would be reduced under cost minimization, whereas those with larger embodied GHG emission intensities would be reduced under GHG emission minimization. For a more detailed understanding of the optimal choices, it is useful to "modify" prices and embodied GHG emission intensities with the consideration of AE content of the virgin sources and yield ratios during alloy steel productions. We now define an indicator that we call the reduction intensity of AE virgin source v with respect to alloy element e in terms of objective function k, p_{ev}^{k}, as follows:

$$p_{ev}^{k} = \frac{b_v^k}{f_{ev} c_{ev}} \ (e \in E \setminus \{\mathrm{Fe}\}, v \in D^{'} \cup M^{'}, k \in K) \qquad \text{(S8)}$$

Note that the yield ratio f_{ev} has only two subscripts representing element e and AE source v, which implies the yield ratio does not depend on which alloy steel to produce, because we do not consider the reduction intensity with respect to iron. For the purpose of comparison, the normalized reduction intensity defined as $p'^{k}_{ev} = p^{k}_{ev} / \max\{p^{k}_{em} | m \in D' \cup M'\}$ is used below. Numerical values were summarized in Table S11. Virgin AE sources having a higher p'^{k}_{ev} were prioritized to be substituted by the AEs derived from parts scrap. Reflecting that p'^{k}_{ev} differ under different optimization objectives, the virgin AE sources chosen also differ. However, for chromium, the same substitution choice was selected since both trends of p'^{k}_{ev} were consistent. Some choices would derive opposite results in terms of the benefits of reduced GHG and the costs, respectively. For example, choosing metallic manganese (Imp), and other nickel sources toward cost minimization would increase GHG emissions because their p'^{k}_{ev} for embodied GHG are low.

Table S11 Reduction intensity of commodities and simplified labels of commodities

			p_{ev}^{k}		p'^{k}_{ev}	
$i \in D' \cup M'$	Simplified label	e	k=GHG	k=Cost	k=GHG	k=Cost
Ferromanganese	FeMn	Mn	11.38	0.17	0.46	0.73
Ferrosilicomanganese	SiMn	Mn	**24.71**	0.23	**1.00**	0.98
Metallic manganese	Metallic Mn	Mn	7.69	**0.23**	0.31	**1.00**
Other Mn sources	Other Mn sources	Mn	0.04	0.05	0.00	0.21
Ferromanganese(imp)	FeMn (Imp)	Mn	1.70	0.16	0.07	0.66
Ferrrosilicomanganese(imp)	SiMn (Imp)	Mn	2.21	0.19	0.09	0.81
Metallic manganese(imp)	Metallic Mn (Imp)	Mn	3.51	**0.23**	0.14	**1.00**
Other Mn sources(imp)	Other Mn sources (Imp)	Mn	0.04	0.05	0.00	0.21
Ferrochromium	FeCr	Cr	15.23	0.35	0.66	0.65
Other Cr sources	Other Cr sources	Cr	**23.19**	**0.54**	**1.00**	**1.00**
Ferrochromium(imp)	FeCr (Imp)	Cr	3.31	0.18	0.14	0.33
Other Cr sources(imp)	Other Cr sources (Imp)	Cr	**23.19**	**0.54**	**1.00**	**1.00**
Ferronickel	FeNi	Ni	12.08	1.53	0.30	0.58
Metallic nickel	Metallic Ni	Ni	14.59	1.67	0.36	0.63
Other Ni sources	Other Ni sources	Ni	8.32	**2.65**	0.20	**1.00**
Ferronickel(imp)	FeNi (Imp)	Ni	**40.89**	2.07	**1.00**	0.78
Metallic nickel(imp)	Metallic Ni (Imp)	Ni	10.90	1.67	0.27	0.63
Other Ni sources(imp)	Other Ni sources (Imp)	Ni	8.32	2.65	0.20	1.00
Ferromolybdenum	FeMo	Mo	**9.45**	11.55	**1.00**	0.88
Molybdenum briquette	Mo Oxide briquette	Mo	2.49	8.89	0.26	0.67
Ferromolybdenum(imp)	FeMo (Imp)	Mo	6.72	**13.19**	0.71	**1.00**
Molybdenum briquette(imp)	Mo Oxide briquette (Imp)	Mo	5.78	11.21	0.61	0.85

Bold values are the highest among the sources of corresponding AE

3.2 Calculation of reduction ratio for the evaluation of the result by multi-objective optimization

In Figures 3 and 4 in the main manuscript, we evaluated the benefits of the optimized parts scrap utilization. The reduction ratio in terms of objective function k, R^k, is defined as follows:

$$R^k = \frac{T^{k\,\mathrm{obs}} - T^{k\,\mathrm{opt}}}{T^{k\,\mathrm{obs}}} \times 100 \;\; (k \in K) \tag{S9}$$

Where $T^{k\,\mathrm{obs}}$ represents the objective function k evaluated at the observed values of variables in 2005. When k is embodied GHG minimization, $T^{k\,\mathrm{obs}}$ is 2649 kt-CO_2eq, and that is 208 billion JPY for the cost minimization. $T^{k\,\mathrm{opt}}$ represents the optimal value of objective function k. We also define reduction ratios for each element as follows:

$$R_e^k = \frac{T_e^{k\,\mathrm{obs}} - T_e^{k\,\mathrm{opt}}}{T^{k\,\mathrm{obs}}} \times 100 \;\; (e \in E, k \in K) \tag{S10}$$

Note that the equality $R^k = \sum_{e \in E} R_e^k$ holds by definition. Numerical results are shown in Table S12-S17. Values indicated in bold font correspond to the points in Figure 4 in the main manuscript.

Table S12 Weights between objective functions and corresponding reduction ratio (total)

Weight		Reduction ratio(%)		Weight		Reduction ratio(%)	
GHG	Cost	GHG	Cost	GHG	Cost	GHG	Cost
0.00	**1.00**	**18.22**	**15.21**	0.51	0.49	28.27	12.86
0.01	**0.99**	**24.12**	**15.20**	0.52	0.48	28.27	12.86
0.02	**0.98**	**27.59**	**14.44**	0.53	0.47	28.27	12.86
0.03	0.97	27.59	14.44	0.54	0.46	28.27	12.86
0.04	0.96	27.59	14.44	0.55	0.45	28.27	12.86
0.05	0.95	27.59	14.44	0.56	0.44	28.27	12.84
0.06	0.94	27.59	14.44	0.57	0.43	28.27	12.84
0.07	0.93	27.59	14.44	0.58	0.42	28.27	12.84
0.08	0.92	27.59	14.44	0.59	0.41	28.27	12.84
0.09	0.91	27.59	14.44	0.60	0.40	28.27	12.84
0.10	0.90	27.59	14.44	0.61	0.39	28.27	12.84
0.11	0.89	27.59	14.44	0.62	0.38	28.27	12.84
0.12	0.88	27.59	14.44	0.63	0.37	28.27	12.84
0.13	0.87	27.59	14.44	0.64	0.36	28.27	12.84
0.14	**0.86**	**28.23**	**13.15**	0.65	0.35	28.27	12.84
0.15	0.85	28.23	13.15	0.66	0.34	28.27	12.84
0.16	0.84	28.23	13.15	0.67	0.33	28.27	12.84
0.17	0.83	28.23	13.15	0.68	0.32	28.27	12.84
0.18	0.82	28.23	13.15	0.69	0.31	28.27	12.84
0.19	0.81	28.23	13.15	0.70	0.30	28.27	12.84
0.20	0.80	28.23	13.15	0.71	0.29	28.27	12.84
0.21	0.79	28.23	13.15	0.72	0.28	28.27	12.84
0.22	0.78	28.23	13.15	0.73	0.27	28.27	12.84
0.23	0.77	28.23	13.15	0.74	0.26	28.27	12.84
0.24	0.76	28.23	13.15	0.75	0.25	28.27	12.84
0.25	0.75	28.23	13.15	0.76	0.24	28.27	12.84
0.26	0.74	28.23	13.15	0.77	0.23	28.27	12.84
0.27	0.73	28.23	13.15	0.78	0.22	28.27	12.84
0.28	0.72	28.23	13.15	0.79	0.21	28.27	12.84
0.29	0.71	28.23	13.15	0.80	0.20	28.27	12.84
0.30	0.70	28.23	13.15	0.81	0.19	28.27	12.84
0.31	0.69	28.23	13.15	0.82	0.18	28.27	12.84
0.32	0.68	28.23	13.15	0.83	0.17	28.27	12.84
0.33	0.67	28.23	13.15	0.84	0.16	28.27	12.84
0.34	0.66	28.23	13.15	0.85	0.15	28.27	12.84
0.35	0.65	28.23	13.15	0.86	0.14	28.27	12.84
0.36	0.64	28.23	13.15	0.87	0.13	28.27	12.84
0.37	0.63	28.23	13.15	0.88	0.12	28.27	12.84
0.38	**0.62**	**28.27**	**12.86**	0.89	0.11	28.27	12.84
0.39	0.61	28.27	12.86	0.90	0.10	28.27	12.84
0.40	0.60	28.27	12.86	0.91	0.09	28.27	12.84
0.41	0.59	28.27	12.86	0.92	0.08	28.27	12.84
0.42	0.58	28.27	12.86	0.93	0.07	28.27	12.84
0.43	0.57	28.27	12.86	0.94	0.06	28.27	12.84
0.44	0.56	28.27	12.86	0.95	0.05	28.27	12.84
0.45	0.55	28.27	12.86	0.96	0.04	28.27	12.84
0.46	0.54	28.27	12.86	0.97	0.03	28.27	12.84
0.47	0.53	28.27	12.86	0.98	0.02	28.27	12.84
0.48	0.52	28.27	12.86	0.99	0.01	28.27	12.84
0.49	0.51	28.27	12.86	1.00	0.00	28.27	12.84
0.50	0.50	28.27	12.86				

Table S13 Weights between objective functions and corresponding reduction ratio (Manganese)

Weight		Reduction ratio(%)		Weight		Reduction ratio(%)	
GHG	Cost	GHG	Cost	GHG	Cost	GHG	Cost
0.00	**1.00**	**0.98**	**0.83**	0.51	0.49	6.91	0.82
0.01	**0.99**	**6.88**	**0.82**	0.52	0.48	6.91	0.82
0.02	**0.98**	**6.91**	**0.82**	0.53	0.47	6.91	0.82
0.03	0.97	6.91	0.82	0.54	0.46	6.91	0.82
0.04	0.96	6.91	0.82	0.55	0.45	6.91	0.82
0.05	0.95	6.91	0.82	0.56	0.44	6.92	0.82
0.06	0.94	6.91	0.82	0.57	0.43	6.92	0.82
0.07	0.93	6.91	0.82	0.58	0.42	6.92	0.82
0.08	0.92	6.91	0.82	0.59	0.41	6.92	0.82
0.09	0.91	6.91	0.82	0.60	0.40	6.92	0.82
0.10	0.90	6.91	0.82	0.61	0.39	6.92	0.82
0.11	0.89	6.91	0.82	0.62	0.38	6.92	0.82
0.12	0.88	6.91	0.82	0.63	0.37	6.92	0.82
0.13	0.87	6.91	0.82	0.64	0.36	6.92	0.82
0.14	**0.86**	**6.91**	**0.82**	0.65	0.35	6.92	0.82
0.15	0.85	6.91	0.82	0.66	0.34	6.92	0.82
0.16	0.84	6.91	0.82	0.67	0.33	6.92	0.82
0.17	0.83	6.91	0.82	0.68	0.32	6.92	0.82
0.18	0.82	6.91	0.82	0.69	0.31	6.92	0.82
0.19	0.81	6.91	0.82	0.70	0.30	6.92	0.82
0.20	0.80	6.91	0.82	0.71	0.29	6.92	0.82
0.21	0.79	6.91	0.82	0.72	0.28	6.92	0.82
0.22	0.78	6.91	0.82	0.73	0.27	6.92	0.82
0.23	0.77	6.91	0.82	0.74	0.26	6.92	0.82
0.24	0.76	6.91	0.82	0.75	0.25	6.92	0.82
0.25	0.75	6.91	0.82	0.76	0.24	6.92	0.82
0.26	0.74	6.91	0.82	0.77	0.23	6.92	0.82
0.27	0.73	6.91	0.82	0.78	0.22	6.92	0.82
0.28	0.72	6.91	0.82	0.79	0.21	6.92	0.82
0.29	0.71	6.91	0.82	0.80	0.20	6.92	0.82
0.30	0.70	6.91	0.82	0.81	0.19	6.92	0.82
0.31	0.69	6.91	0.82	0.82	0.18	6.92	0.82
0.32	0.68	6.91	0.82	0.83	0.17	6.92	0.82
0.33	0.67	6.91	0.82	0.84	0.16	6.92	0.82
0.34	0.66	6.91	0.82	0.85	0.15	6.92	0.82
0.35	0.65	6.91	0.82	0.86	0.14	6.92	0.82
0.36	0.64	6.91	0.82	0.87	0.13	6.92	0.82
0.37	0.63	6.91	0.82	0.88	0.12	6.92	0.82
0.38	**0.62**	**6.91**	**0.82**	0.89	0.11	6.92	0.82
0.39	0.61	6.91	0.82	0.90	0.10	6.92	0.82
0.40	0.60	6.91	0.82	0.91	0.09	6.92	0.82
0.41	0.59	6.91	0.82	0.92	0.08	6.92	0.82
0.42	0.58	6.91	0.82	0.93	0.07	6.92	0.82
0.43	0.57	6.91	0.82	0.94	0.06	6.92	0.82
0.44	0.56	6.91	0.82	0.95	0.05	6.92	0.82
0.45	0.55	6.91	0.82	0.96	0.04	6.92	0.82
0.46	0.54	6.91	0.82	0.97	0.03	6.92	0.82
0.47	0.53	6.91	0.82	0.98	0.02	6.92	0.82
0.48	0.52	6.91	0.82	0.99	0.01	6.92	0.82
0.49	0.51	6.91	0.82	1.00	0.00	6.92	0.82
0.50	0.50	6.91	0.82				

Table S14 Weights between objective functions and corresponding reduction ratio (chromium)

Weight		Reduction ratio(%)		Weight		Reduction ratio(%)	
GHG	Cost	GHG	Cost	GHG	Cost	GHG	Cost
0.00	**1.00**	**10.78**	**3.50**	0.51	0.49	10.78	3.50
0.01	**0.99**	**10.78**	**3.50**	0.52	0.48	10.78	3.50
0.02	**0.98**	**10.78**	**3.50**	0.53	0.47	10.78	3.50
0.03	0.97	10.78	3.50	0.54	0.46	10.78	3.50
0.04	0.96	10.78	3.50	0.55	0.45	10.78	3.50
0.05	0.95	10.78	3.50	0.56	0.44	10.78	3.50
0.06	0.94	10.78	3.50	0.57	0.43	10.78	3.50
0.07	0.93	10.78	3.50	0.58	0.42	10.78	3.50
0.08	0.92	10.78	3.50	0.59	0.41	10.78	3.50
0.09	0.91	10.78	3.50	0.60	0.40	10.78	3.50
0.10	0.90	10.78	3.50	0.61	0.39	10.78	3.50
0.11	0.89	10.78	3.50	0.62	0.38	10.78	3.50
0.12	0.88	10.78	3.50	0.63	0.37	10.78	3.50
0.13	0.87	10.78	3.50	0.64	0.36	10.78	3.50
0.14	**0.86**	**10.78**	**3.50**	0.65	0.35	10.78	3.50
0.15	0.85	10.78	3.50	0.66	0.34	10.78	3.50
0.16	0.84	10.78	3.50	0.67	0.33	10.78	3.50
0.17	0.83	10.78	3.50	0.68	0.32	10.78	3.50
0.18	0.82	10.78	3.50	0.69	0.31	10.78	3.50
0.19	0.81	10.78	3.50	0.70	0.30	10.78	3.50
0.20	0.80	10.78	3.50	0.71	0.29	10.78	3.50
0.21	0.79	10.78	3.50	0.72	0.28	10.78	3.50
0.22	0.78	10.78	3.50	0.73	0.27	10.78	3.50
0.23	0.77	10.78	3.50	0.74	0.26	10.78	3.50
0.24	0.76	10.78	3.50	0.75	0.25	10.78	3.50
0.25	0.75	10.78	3.50	0.76	0.24	10.78	3.50
0.26	0.74	10.78	3.50	0.77	0.23	10.78	3.50
0.27	0.73	10.78	3.50	0.78	0.22	10.78	3.50
0.28	0.72	10.78	3.50	0.79	0.21	10.78	3.50
0.29	0.71	10.78	3.50	0.80	0.20	10.78	3.50
0.30	0.70	10.78	3.50	0.81	0.19	10.78	3.50
0.31	0.69	10.78	3.50	0.82	0.18	10.78	3.50
0.32	0.68	10.78	3.50	0.83	0.17	10.78	3.50
0.33	0.67	10.78	3.50	0.84	0.16	10.78	3.50
0.34	0.66	10.78	3.50	0.85	0.15	10.78	3.50
0.35	0.65	10.78	3.50	0.86	0.14	10.78	3.50
0.36	0.64	10.78	3.50	0.87	0.13	10.78	3.50
0.37	0.63	10.78	3.50	0.88	0.12	10.78	3.50
0.38	**0.62**	**10.78**	**3.50**	0.89	0.11	10.78	3.50
0.39	0.61	10.78	3.50	0.90	0.10	10.78	3.50
0.40	0.60	10.78	3.50	0.91	0.09	10.78	3.50
0.41	0.59	10.78	3.50	0.92	0.08	10.78	3.50
0.42	0.58	10.78	3.50	0.93	0.07	10.78	3.50
0.43	0.57	10.78	3.50	0.94	0.06	10.78	3.50
0.44	0.56	10.78	3.50	0.95	0.05	10.78	3.50
0.45	0.55	10.78	3.50	0.96	0.04	10.78	3.50
0.46	0.54	10.78	3.50	0.97	0.03	10.78	3.50
0.47	0.53	10.78	3.50	0.98	0.02	10.78	3.50
0.48	0.52	10.78	3.50	0.99	0.01	10.78	3.50
0.49	0.51	10.78	3.50	1.00	0.00	10.78	3.50
0.50	0.50	10.78	3.50				

Table S15 Weights between objective functions and corresponding reduction ratio (nickel)

Weight		Reduction ratio(%)		Weight		Reduction ratio(%)	
GHG	Cost	GHG	Cost	GHG	Cost	GHG	Cost
0.00	**1.00**	**1.73**	**7.02**	0.51	0.49	5.80	4.97
0.01	**0.99**	**1.73**	**7.02**	0.52	0.48	5.80	4.97
0.02	**0.98**	**5.16**	**6.26**	0.53	0.47	5.80	4.97
0.03	0.97	5.16	6.26	0.54	0.46	5.80	4.97
0.04	0.96	5.16	6.26	0.55	0.45	5.80	4.97
0.05	0.95	5.16	6.26	0.56	0.44	5.80	4.96
0.06	0.94	5.16	6.26	0.57	0.43	5.80	4.96
0.07	0.93	5.16	6.26	0.58	0.42	5.80	4.96
0.08	0.92	5.16	6.26	0.59	0.41	5.80	4.96
0.09	0.91	5.16	6.26	0.60	0.40	5.80	4.96
0.10	0.90	5.16	6.26	0.61	0.39	5.80	4.96
0.11	0.89	5.16	6.26	0.62	0.38	5.80	4.96
0.12	0.88	5.16	6.26	0.63	0.37	5.80	4.96
0.13	0.87	5.16	6.26	0.64	0.36	5.80	4.96
0.14	**0.86**	**5.80**	**4.97**	0.65	0.35	5.80	4.96
0.15	0.85	5.80	4.97	0.66	0.34	5.80	4.96
0.16	0.84	5.80	4.97	0.67	0.33	5.80	4.96
0.17	0.83	5.80	4.97	0.68	0.32	5.80	4.96
0.18	0.82	5.80	4.97	0.69	0.31	5.80	4.96
0.19	0.81	5.80	4.97	0.70	0.30	5.80	4.96
0.20	0.80	5.80	4.97	0.71	0.29	5.80	4.96
0.21	0.79	5.80	4.97	0.72	0.28	5.80	4.96
0.22	0.78	5.80	4.97	0.73	0.27	5.80	4.96
0.23	0.77	5.80	4.97	0.74	0.26	5.80	4.96
0.24	0.76	5.80	4.97	0.75	0.25	5.80	4.96
0.25	0.75	5.80	4.97	0.76	0.24	5.80	4.96
0.26	0.74	5.80	4.97	0.77	0.23	5.80	4.96
0.27	0.73	5.80	4.97	0.78	0.22	5.80	4.96
0.28	0.72	5.80	4.97	0.79	0.21	5.80	4.96
0.29	0.71	5.80	4.97	0.80	0.20	5.80	4.96
0.30	0.70	5.80	4.97	0.81	0.19	5.80	4.96
0.31	0.69	5.80	4.97	0.82	0.18	5.80	4.96
0.32	0.68	5.80	4.97	0.83	0.17	5.80	4.96
0.33	0.67	5.80	4.97	0.84	0.16	5.80	4.96
0.34	0.66	5.80	4.97	0.85	0.15	5.80	4.96
0.35	0.65	5.80	4.97	0.86	0.14	5.80	4.96
0.36	0.64	5.80	4.97	0.87	0.13	5.80	4.96
0.37	0.63	5.80	4.97	0.88	0.12	5.80	4.96
0.38	**0.62**	**5.80**	**4.97**	0.89	0.11	5.80	4.96
0.39	0.61	5.80	4.97	0.90	0.10	5.80	4.96
0.40	0.60	5.80	4.97	0.91	0.09	5.80	4.96
0.41	0.59	5.80	4.97	0.92	0.08	5.80	4.96
0.42	0.58	5.80	4.97	0.93	0.07	5.80	4.96
0.43	0.57	5.80	4.97	0.94	0.06	5.80	4.96
0.44	0.56	5.80	4.97	0.95	0.05	5.80	4.96
0.45	0.55	5.80	4.97	0.96	0.04	5.80	4.96
0.46	0.54	5.80	4.97	0.97	0.03	5.80	4.96
0.47	0.53	5.80	4.97	0.98	0.02	5.80	4.96
0.48	0.52	5.80	4.97	0.99	0.01	5.80	4.96
0.49	0.51	5.80	4.97	1.00	0.00	5.80	4.96
0.50	0.50	5.80	4.97				

Table S16 Weights between objective functions and corresponding reduction ratio (molybdenum)

Weight		Reduction ratio(%)		Weight		Reduction ratio(%)	
GHG	Cost	GHG	Cost	GHG	Cost	GHG	Cost
0.00	**1.00**	**0.11**	**2.67**	0.51	0.49	0.15	2.38
0.01	**0.99**	**0.11**	**2.67**	0.52	0.48	0.15	2.38
0.02	**0.98**	**0.11**	**2.67**	0.53	0.47	0.15	2.38
0.03	0.97	0.11	2.67	0.54	0.46	0.15	2.38
0.04	0.96	0.11	2.67	0.55	0.45	0.15	2.38
0.05	0.95	0.11	2.67	0.56	0.44	0.15	2.37
0.06	0.94	0.11	2.67	0.57	0.43	0.15	2.37
0.07	0.93	0.11	2.67	0.58	0.42	0.15	2.37
0.08	0.92	0.11	2.67	0.59	0.41	0.15	2.37
0.09	0.91	0.11	2.67	0.60	0.40	0.15	2.37
0.10	0.90	0.11	2.67	0.61	0.39	0.15	2.37
0.11	0.89	0.11	2.67	0.62	0.38	0.15	2.37
0.12	0.88	0.11	2.67	0.63	0.37	0.15	2.37
0.13	0.87	0.11	2.67	0.64	0.36	0.15	2.37
0.14	**0.86**	**0.11**	**2.67**	0.65	0.35	0.15	2.37
0.15	0.85	0.11	2.67	0.66	0.34	0.15	2.37
0.16	0.84	0.11	2.67	0.67	0.33	0.15	2.37
0.17	0.83	0.11	2.67	0.68	0.32	0.15	2.37
0.18	0.82	0.11	2.67	0.69	0.31	0.15	2.37
0.19	0.81	0.11	2.67	0.70	0.30	0.15	2.37
0.20	0.80	0.11	2.67	0.71	0.29	0.15	2.37
0.21	0.79	0.11	2.67	0.72	0.28	0.15	2.37
0.22	0.78	0.11	2.67	0.73	0.27	0.15	2.37
0.23	0.77	0.11	2.67	0.74	0.26	0.15	2.37
0.24	0.76	0.11	2.67	0.75	0.25	0.15	2.37
0.25	0.75	0.11	2.67	0.76	0.24	0.15	2.37
0.26	0.74	0.11	2.67	0.77	0.23	0.15	2.37
0.27	0.73	0.11	2.67	0.78	0.22	0.15	2.37
0.28	0.72	0.11	2.67	0.79	0.21	0.15	2.37
0.29	0.71	0.11	2.67	0.80	0.20	0.15	2.37
0.30	0.70	0.11	2.67	0.81	0.19	0.15	2.37
0.31	0.69	0.11	2.67	0.82	0.18	0.15	2.37
0.32	0.68	0.11	2.67	0.83	0.17	0.15	2.37
0.33	0.67	0.11	2.67	0.84	0.16	0.15	2.37
0.34	0.66	0.11	2.67	0.85	0.15	0.15	2.37
0.35	0.65	0.11	2.67	0.86	0.14	0.15	2.37
0.36	0.64	0.11	2.67	0.87	0.13	0.15	2.37
0.37	0.63	0.11	2.67	0.88	0.12	0.15	2.37
0.38	**0.62**	**0.15**	**2.38**	0.89	0.11	0.15	2.37
0.39	0.61	0.15	2.38	0.90	0.10	0.15	2.37
0.40	0.60	0.15	2.38	0.91	0.09	0.15	2.37
0.41	0.59	0.15	2.38	0.92	0.08	0.15	2.37
0.42	0.58	0.15	2.38	0.93	0.07	0.15	2.37
0.43	0.57	0.15	2.38	0.94	0.06	0.15	2.37
0.44	0.56	0.15	2.38	0.95	0.05	0.15	2.37
0.45	0.55	0.15	2.38	0.96	0.04	0.15	2.37
0.46	0.54	0.15	2.38	0.97	0.03	0.15	2.37
0.47	0.53	0.15	2.38	0.98	0.02	0.15	2.37
0.48	0.52	0.15	2.38	0.99	0.01	0.15	2.37
0.49	0.51	0.15	2.38	1.00	0.00	0.15	2.37
0.50	0.50	0.15	2.38				

Table S17 Weights between objective functions and corresponding reduction ratio (iron)

Weight		Reduction ratio(%)		Weight		Reduction ratio(%)	
GHG	Cost	GHG	Cost	GHG	Cost	GHG	Cost
0.00	**1.00**	**4.63**	**1.19**	0.51	0.49	4.63	1.19
0.01	**0.99**	**4.63**	**1.19**	0.52	0.48	4.63	1.19
0.02	**0.98**	**4.63**	**1.19**	0.53	0.47	4.63	1.19
0.03	0.97	4.63	1.19	0.54	0.46	4.63	1.19
0.04	0.96	4.63	1.19	0.55	0.45	4.63	1.19
0.05	0.95	4.63	1.19	0.56	0.44	4.63	1.19
0.06	0.94	4.63	1.19	0.57	0.43	4.63	1.19
0.07	0.93	4.63	1.19	0.58	0.42	4.63	1.19
0.08	0.92	4.63	1.19	0.59	0.41	4.63	1.19
0.09	0.91	4.63	1.19	0.60	0.40	4.63	1.19
0.10	0.90	4.63	1.19	0.61	0.39	4.63	1.19
0.11	0.89	4.63	1.19	0.62	0.38	4.63	1.19
0.12	0.88	4.63	1.19	0.63	0.37	4.63	1.19
0.13	0.87	4.63	1.19	0.64	0.36	4.63	1.19
0.14	**0.86**	**4.63**	**1.19**	0.65	0.35	4.63	1.19
0.15	0.85	4.63	1.19	0.66	0.34	4.63	1.19
0.16	0.84	4.63	1.19	0.67	0.33	4.63	1.19
0.17	0.83	4.63	1.19	0.68	0.32	4.63	1.19
0.18	0.82	4.63	1.19	0.69	0.31	4.63	1.19
0.19	0.81	4.63	1.19	0.70	0.30	4.63	1.19
0.20	0.80	4.63	1.19	0.71	0.29	4.63	1.19
0.21	0.79	4.63	1.19	0.72	0.28	4.63	1.19
0.22	0.78	4.63	1.19	0.73	0.27	4.63	1.19
0.23	0.77	4.63	1.19	0.74	0.26	4.63	1.19
0.24	0.76	4.63	1.19	0.75	0.25	4.63	1.19
0.25	0.75	4.63	1.19	0.76	0.24	4.63	1.19
0.26	0.74	4.63	1.19	0.77	0.23	4.63	1.19
0.27	0.73	4.63	1.19	0.78	0.22	4.63	1.19
0.28	0.72	4.63	1.19	0.79	0.21	4.63	1.19
0.29	0.71	4.63	1.19	0.80	0.20	4.63	1.19
0.30	0.70	4.63	1.19	0.81	0.19	4.63	1.19
0.31	0.69	4.63	1.19	0.82	0.18	4.63	1.19
0.32	0.68	4.63	1.19	0.83	0.17	4.63	1.19
0.33	0.67	4.63	1.19	0.84	0.16	4.63	1.19
0.34	0.66	4.63	1.19	0.85	0.15	4.63	1.19
0.35	0.65	4.63	1.19	0.86	0.14	4.63	1.19
0.36	0.64	4.63	1.19	0.87	0.13	4.63	1.19
0.37	0.63	4.63	1.19	0.88	0.12	4.63	1.19
0.38	**0.62**	**4.63**	**1.19**	0.89	0.11	4.63	1.19
0.39	0.61	4.63	1.19	0.90	0.10	4.63	1.19
0.40	0.60	4.63	1.19	0.91	0.09	4.63	1.19
0.41	0.59	4.63	1.19	0.92	0.08	4.63	1.19
0.42	0.58	4.63	1.19	0.93	0.07	4.63	1.19
0.43	0.57	4.63	1.19	0.94	0.06	4.63	1.19
0.44	0.56	4.63	1.19	0.95	0.05	4.63	1.19
0.45	0.55	4.63	1.19	0.96	0.04	4.63	1.19
0.46	0.54	4.63	1.19	0.97	0.03	4.63	1.19
0.47	0.53	4.63	1.19	0.98	0.02	4.63	1.19
0.48	0.52	4.63	1.19	0.99	0.01	4.63	1.19
0.49	0.51	4.63	1.19	1.00	0.00	4.63	1.19
0.50	0.50	4.63	1.19				

3.3 Sensitivity of scrap mass on the benefits

The optimization has been done based on stable state throughout the study. In this section, the results of a sensitivity analysis would be presented to show the sensitivity to a change in scrap mass of the benefits (i.e., embodied GHG and purchase cost of virgin sources). The reduction ratios in the benefits were evaluated for the cases where the mass of each parts scrap increased or decreased by 10%. Instead of solving a linear program for each case, we used the dual variables that we solved for the base case.

Figure S1 (a) and (b) shows the variations of reduction ratios on embodied GHG and the cost, respectively, against the change of mass of parts scrap. The trends looked almost consistent in both objective functions. When supplied mass of exhaust parts increased and decreased 10%, the reduction ratios changed ±0.35 points and ±0.65 points from base cases in terms of embodied GHG and the cost, respectively whereas the change in mass of other kinds of parts scrap looked less sensitive against the benefits. Exhaust parts contain much AEs sharing more than 50% of AE contents occurring in all parts scrap. Therefore, 10% change in the supply of exhaust parts results in 5% change in the AE supply from parts scrap. However, the change in the benefits were much less than 5% in both objective functions. This result can be explained by Figure 3 in the main manuscript and Table S11. In terms of chromium, nickel and molybdenum, which were mainly derived from exhaust parts, consumption of virgin sources having the highest intensities were entirely reduced. Consequently, subsequently highest intensities of virgin sources were reduced. For example, for chromium, until the third highest intensities of virgin sources (i.e., domestic and imported Other Cr sources, and FeCr) were entirely reduced, and FeCr (imp) having the lowest intensities was slightly reduced in both objective function as shown in Figure 3. When ±10% change in exhaust parts supply occurred, change in reduction was occurred only in FeCr (Imp) consumption. As a consequence, change in the embodied GHG and the cost became small because only small benefit could be obtained by the reduction of the consumption of FeCr (Imp) having the lowest intensities. Considering this result of sensitivity analysis, it would be able to predict that even if masses of

AEs derived from ELV steel scrap moderately increased from the original masses in this study, the increase of the benefits would not increase so much dramatically.

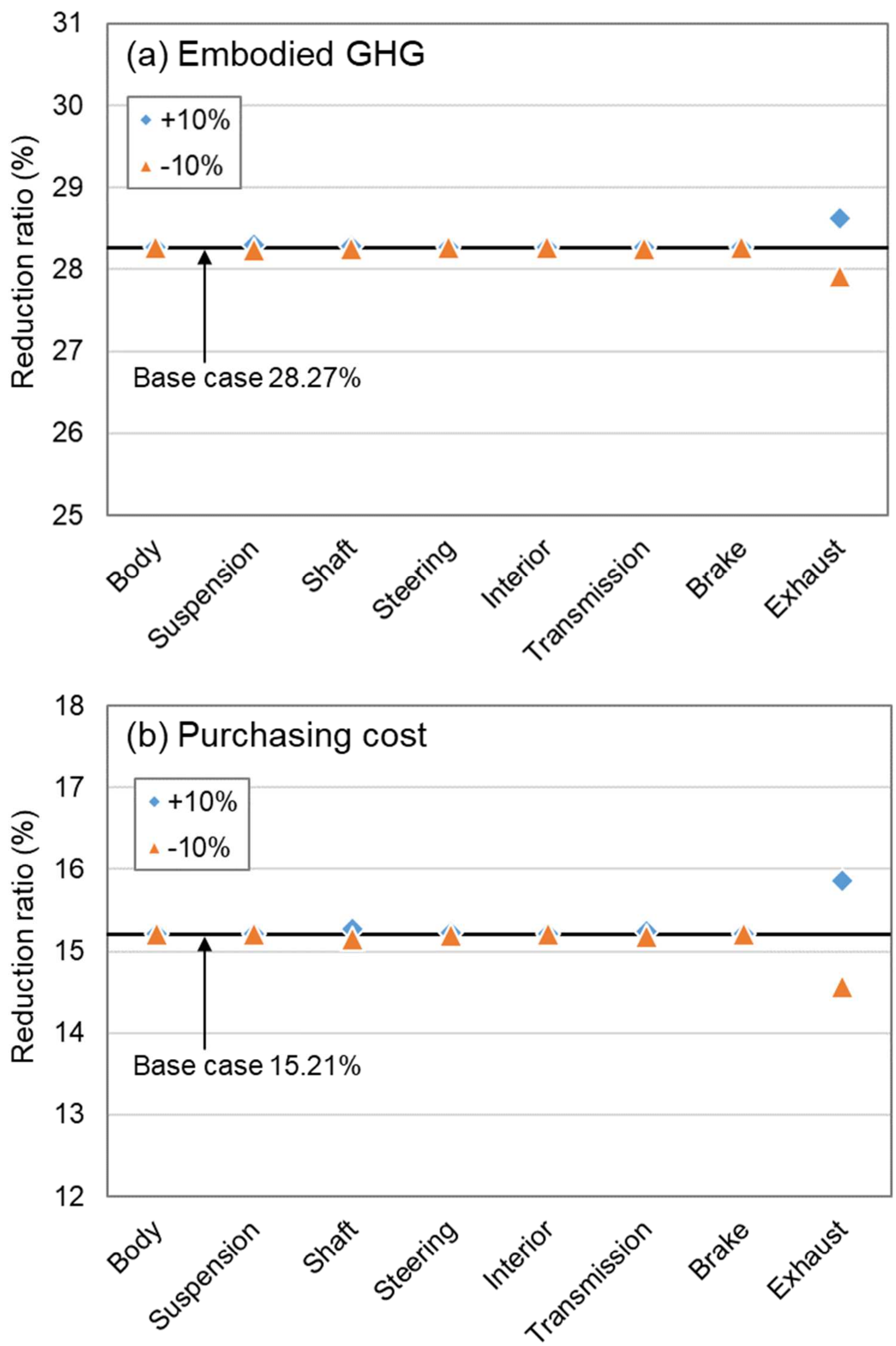

Figure S1 Changes in reduction ratios against ±10% differences in suppling mass of each parts scrap in terms of (a) embodied GHG and (b) purchasing cost for virgin AE sources

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