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Research article

GHG impacts of an innovative separation process (three-way sorting process) for horizontal recycling of aluminum

Kotaro Kawajiri [1], Michio Kobayashi [1] and Shigeki Koyanaka [2]

1. AIZOTH. Inc 2nd Floor, Daiwa Roynet Hotel Tsukuba Bldg, 1-5-7 Azuma, Tsukuba, IBARAKI 305-0031, Japan
2. National Institute of Advanced Industrial Science and Technology, Onogawa 16-1, Tsukuba City, Ibaraki prefecture, 305-8569, Japan

* **Correspondence:** Email: kotaro.kawajiri@aizoth.com; Tel: +81-(50)3695-9622.

Abstract: Life Cycle Assessment (LCA) was conducted in screening wrought aluminum from shredded automotive scrap using sorting technology. This technology comprises Pre-sorting, ECS (Eddy-current separation) sorting, and LIBS (Laser Induced Breakdown Spectroscopy) sorting, referred to as three-way sorting. Shredded automobile scrap contains wrought aluminum, cast aluminum, zinc, plastics, and other materials. Three-way sorting initially screens non-aluminum by Pre-sorting and ECS sorting, followed by LIBS sorting to separate wrought and cast aluminum. LCA showed that greenhouse gas (GHG) emissions to obtain wrought aluminum from the scrap were 0.168 kg-CO_2 eq/kg. Further, GHG emissions decreased to −0.24 kg-CO_2 eq/kg if reclaimed cast aluminum was reused and its GHG emissions were credited. Since GHG emissions of virgin aluminum were 9.93 kg-CO_2 eq/kg, GHG emissions by three-way sorting were far below. In terms of cost, it was initially 259 JPY/kg to produce reclaimed wrought aluminum. However, under an improved scenario reflecting real manufacturing conditions, the study showed a potential to reduce its cost to 107 JPY/kg.

Keywords: Recycle; Wrought aluminum; LCA; Greenhouse gas (GHG); ECS sorting; LIBS sorting

1. Introduction

Recycling wrought aluminum is gaining industry attention. Supply of aluminum is uncertain due to economic and geopolitical reasons. Securing aluminum supply is attracting critical attention. Regarding demand, wrought alloys (impurity content up to 10%) represent two-thirds while cast alloys (with much higher impurity content) represent one-third of the global aluminum demand [1]. Use of wrought aluminum is expected to increase sharply over the next two decades due to its adoption in the automotive market. Cars contain about 8 % wrought aluminum by weight, and it is forecasted to reach 16 % by 2028 [2]. This increase of wrought aluminum usage will result in a substantial rise in the amount of wrought aluminum scrap [3].

In terms of recycling, wrought aluminum is mainly processed into cast alloys rather than wrought alloys [4]. The reason is that cast alloys having higher compositional tolerance for impurities make them unsuitable for recycling anything other than cast alloys [5]. Down-cycling mixed aluminum scrap into recycle-friendly cast alloys is a common strategy today, but the future market for these products is uncertain due to the emergence of electric vehicles [6]. The wide spread of electric vehicles will result in a decrease in cast alloy demand. Cullen and Allwood (2013) [1] estimated that globally, every year, 6.1 Mt of wrought aluminum scrap was downgraded into cast alloys. Modaresi and Müller (2012) [4] forecasted that a continuing the above-mentioned strategy would result in non-recyclable casting scrap surplus in 2018, with an uncertain margin of about five years. Therefore, the argument arises that the amount of recycled wrought aluminum from consumer scrap should increase and be qualified for future sustainable solutions [7]. This would be an important future trend in developing new wrought alloys to meet various customer requirements [8,9] and can be the game changer in the aluminum industry.

Reducing greenhouse gas (GHG) emissions in recycling wrought aluminum is also crucial as GHG emissions from virgin aluminum production are high (9.93 kg-CO_2 eq/kg) compared to conventional materials like steel (2.11 kg-CO_2/kg) [10]. Thus, with the increasing demand for wrought aluminum and its expected scrap, it is necessary to construct a sustainable recycling system to support wrought aluminum demand with lower GHG emissions.

Several sorting technologies have been used to screen scrap aluminum to the required alloy level (e.g., 5000 or 6000 series) [11]. Among them, Laser-Induced Breakdown Spectroscopy (LIBS) is a promising one as it can determine the concentrations of alloying elements and is widely used in industry today. For instance, Japanese bullet trains are made from LIBS-sorted recycled aluminum from older generation bullet trains [12]. However, LIBS sorting alone does not accurately screen desired wrought aluminum from mixed scrap including non-aluminum. Therefore, a new screening method combining pre-sorting, Eddy Current Separation (ECS), and LIBS sorting (three-way sorting process) was developed. Pre-sorting and ECS sorting separate aluminum from non-aluminum. After removing almost all non-aluminum, LIBS sorting separates wrought from cast aluminum and remaining non-aluminum scrap. Cast aluminum can be reused as cast aluminum. With the optimized settings in each sorting technology, high-quality wrought aluminum can be screened efficiently. This three-way sorting process is the most efficient in reclaiming wrought aluminum from scrap without re-melting. In general, re-melting process consumes a lot of electricity resulting in higher GHG emissions. In this paper, we review the capability of three-way sorting process and conduct Life Cycle Assessment (LCA) to evaluate its environmental friendliness.

Many LCA studies on aluminum recycling have been conducted by organizations such as the Japan Aluminum Association (2019) [13] and European Aluminum (2020) [14]. However, few LCA studies have been done specifically for sorting technologies. One such study is one by Bjørnbet (2014) [15], who compared the environmental impacts for an aluminum Body-in-White (BiW) made from three material inputs, i.e., primary aluminum, closed-loop recycled old BiW, and open loop recycled end of life vehicle scrap. This analysis included a collection process of the scrap in LCA. The work mainly focused on the comparison of the impact categories among three types of inputs. No numerical analysis in GWP, i.e., xx kg-CO_2 eq in each input was conducted. Another one is by Eynde et. al (2024) [16] who performed an LCA on three scrap treatments, the traditional Hoopes refining process, a novel low-energy Hoopes process, and LIBS sorting. The author concluded that LIBS sorting was the promising technology. However, the researchers focused on the comparison of the impact categories among three treatments. No numerical analysis in GWP was included. From the previous research, the identified research gap is that numerical analysis in GWP to understand the climate impact was not conducted in scrap treatment and recycling process. Therefore, it is meaningful and necessary to assess how much the environment impact, GWP, can be reduced in wrought aluminum recycling by three-way sorting.

In this paper, an LCA is conducted for three-way sorting technology from shredded automobile scrap, which includes more than just aluminum. We set the objectives of this study to 1) prove three-way sorting technology effectively reclaims wrought aluminum from scrap, 2) assess GHG emissions in reclaiming 1 kg of wrought aluminum based on a cradle-to-gate approach, and 3) estimate the cost of reclaiming 1 kg of wrought aluminum from scrap. This three-way sorting technology was developed by the National Institute of Advanced Industrial Science and Technologies.

The working mechanisms of ECS and LIBS sorting are described in more detail. The basic principle of ECS sorting is that when a permanent magnet passes over a conductive metal object, electric charge within the metal experiences a net magnetic force [17]. This causes the charges to flow in distinct swirling patterns, commonly referred to as eddy currents. If the magnetic force is strong enough and the relative motion is quick enough, this force can significantly accelerate the metal particles [18]. Metals with varying conductivity will produce varying eddy currents and will, therefore, be thrown different distances. By setting up collection bins at these varying distances, it is possible to separate the scrap stream by base metal [19]. LIBS sorting uses a pulse laser and optical emission spectroscopy, showing a great capability for sorting wrought and cast aluminum. A sensor detects a piece of the scrap and activates a pulse laser. The laser hits the metal surface and produces atomic emissions. The optical spectra are read by a polychromator and a photodiode detector, which sends a signal to a computer system [20]. The system then directs the scrap to an appropriate bin using a mechanical arm.

2. Materials and methods

Life Cycle Assessment (LCA) with a Cradle-to-Gate approach is conducted in this paper. The system boundary of wrought aluminum recycling is shown in Figure 1.

Shredded automobile scrap is sorted by Pre-sorting, ECS sorting, and LIBS sorting. At the end of LIBS sorting, cast and wrought aluminum appear as the output. Sorted wrought aluminum goes through rinsing, re-melting, refining, and semi-fabrication [21] to be used as commercial quality wrought aluminum. Semi-fabrication process includes production of aluminum sheets. In this study, our unique sorting process is analyzed. The process after LIBS sorting is the same for any other sorting methods. Therefore, those processes are excluded. The sorting process analyzed in this study is highlighted in grey color in Figure 1.

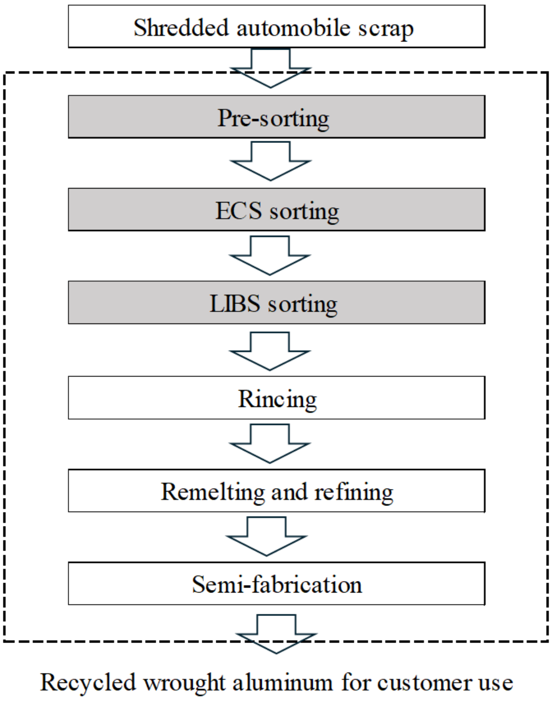


Figure 1. System boundary of recycling wrought aluminum.

There are three stages in this sorting process: Pre-sorting, ECS sorting, and LIBS sorting. Shredded automobile scrap goes into Pre-soring. In Pre-sorting, unwanted materials such as plastic, zinc, copper, capacitors, PCB, and aluminum alloys are removed. However, the output from Pre-sorting includes those unwanted materials. Next, most of those unwanted materials are removed by ECS sorting. The output from ECS sorting consists of a small amount of non-aluminum, cast, and wrought aluminum alloys. As the last step, LIBS sorting removes non-aluminum materials. In addition, LIBS sorting separates cast and wrought aluminum alloys. The final output is cast and wrought aluminum alloys.

The functional unit is 1 kg of reclaimed wrought aluminum. The final output from LIBS sorting consists of both cast and wrought aluminum with approximately 74% being wrought aluminum. While sorted cast aluminum can be recycled, it is uncertain if the quality is sufficient to meet market requirements. We discuss the scenario where sorted cast alloy is recycled in the discussion section.

Inventory data was created based on 1,000 kg of screened wrought aluminum output from shredded automotive sources. Plastic waste from Pre-sorting, ECS sorting, and LIBS sorting are landfilled. GHG emissions for other non-plastic waste are not assigned because those can be recycled and reused. In this study, GHG emissions of 0.002 kg-CO_2 eq/kg are assigned to the input scrap for Pre-sorting according to the IDEA_v2.1.3 database [10].

3. Results

3.1. GHG emissions

The output from Pre-sorting is fed into ECS sorting, and the output from ECS sorting is then fed into LIBS sorting. Inventory data including GHG emissions and the cost of each sorting process are shown in Table 1. Equipment specifications of Pre-sorting, ECS sorting, and LIBS sorting are shown in Table 2. Those are obtained from the National Institute of Advanced Industrial Science and Technologies.

Table 1. Inventory data and GHG emissions and the cost of each sorting process.

	Process	Materials	Unit	Production scale 1,000 kg	Production scale normalized to 1.0 kg	GHG emissions kg-CO_2 eq/kg	Cost JPY/kg
Pre-sorting	Input	Equipment	JPY	11,676.72	8.05	0.0543	8.05
		Facility	m^2	0.00	0.00	0.0015	0.01
		Labor	JPY	167,070.58	115.13	0.0000	115.13
		AL alloy	kg	2,591.30	1.79	0.0035	70.49
		Copper alloy	kg	204.58	0.14	0.0003	
		Zink alloy	kg	136.38	0.09	0.0002	
		PCB	kg	272.77	0.19	0.0004	
		Capacitor	kg	68.19	0.05	0.0001	
		Plastics	kg	136.38	0.09	0.0002	
	Energy	Electricity	kWh	83.54	0.06	0.0349	1.01
	Waste	Plastics	kg	40.92	0.03	0.0002	0.38
		Copper alloy	kg	61.37	0.04	0.0000	0.00
		Zink alloy	kg	40.92	0.03	0.0000	0.00
		PCB	kg	218.21	0.15	0.0000	0.00
		Capacitor	kg	54.55	0.04	0.0000	0.00
		AL alloy	kg	777.39	0.54	0.0000	0.00
	Output	Plastics	kg	95.47	0.07	0.0000	0.00
		Copper alloy	kg	143.20	0.10	0.0000	0.00
		Zink alloy	kg	95.47	0.07	0.0000	0.00
		PCB	kg	54.55	0.04	0.0000	0.00
		Capacitor	kg	13.64	0.01	0.0000	0.00
		AL alloy	kg	1,813.91	1.25	0.0000	0.00

(a) Pre-sorting

ECS sorting	Process	Materials	Unit	Production scale 1,000 kg	Production scale normalized to 1.0 kg	GHG emissions kg-CO_2 eq/kg	Cost JPY/kg
	Input	Equipment	JPY	2,457.67	1.69	0.0114	1.69
		Facility	m^2	0.00	0.00	0.0011	0.01
		Labor	JPY	77,568.48	53.45	0.0000	53.45
		AL alloy	kg	1,813.91	1.25	0.0000	0.00
		Copper alloy	kg	143.20	0.10	0.0000	0.00
		Zink alloy	kg	95.47	0.07	0.0000	0.00
		PCB	kg	54.55	0.04	0.0000	0.00
		Capacitor	kg	13.64	0.01	0.0000	0.00
		Plastics	kg	95.47	0.07	0.0000	0.00
	Energy	Electricity	kWh	119.68	0.08	0.0500	1.45
	Waste	AL alloy	kg	362.78	0.25	0.0000	0.00
		Copper alloy	kg	143.20	0.10	0.0000	0.00
		Zink alloy	kg	95.47	0.07	0.0000	0.00
		PCB	kg	54.55	0.04	0.0000	0.00
		Capacitor	kg	13.64	0.01	0.0000	0.00
		Plastics	kg	95.47	0.07	0.0005	0.88
	Output	AL and Non AL	kg	1,451.13	1.00	0.0000	0.00

(b) ECS sorting

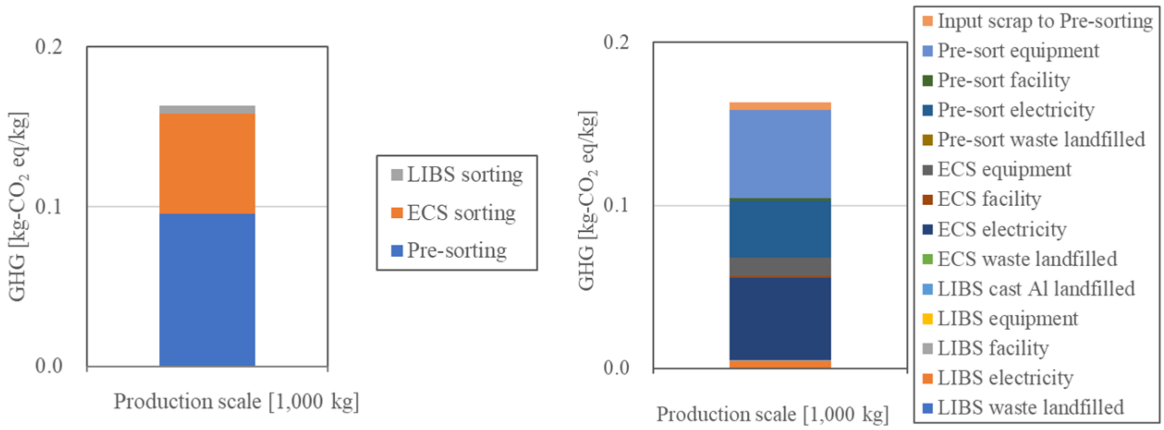
LIBS sorting	Process	Materials	Unit	Production scale 1,000 kg	Production scale normalized to 1.0 kg	GHG emissions kg-CO_2 eq/kg	Cost JPY/kg
	Input	Equipment	JPY	730.35	0.73	0.0049	0.73
		Facility	m^2	0.00	0.00	0.0002	0.00
		Labor	JPY	3,918.71	3.92	0.0000	3.92
		AL and Non AL	kg	1,451,13	1.45	0.0000	0.00
	Energy	Electricity	kWh	6.61	0.01	0.0040	0.12
	Waste	Non AL	kg	94.09	0.09	0.0007	1.25
	Output	Cast aluminum	kg	356.96	0.36	0.0000	0.00
		Wrought aluminum	kg	1,000.00	1.00	0.0000	0.00

(c) LIBS sorting

Table 2. Equipment specification.

	Pre-sorting	ECS sorting	LIBS sorting
Capacity (kg)	100	65	360
Power requirement (kW)	1.75	5.40	5.90
Processing time (hour)	1.40	0.65	0.28
Price (JPY)	15,000,000	6,800,000	4,000,000

To produce 1,000 kg of reclaimed wrought aluminum, 3,410 kg of scrap, which is the sum of the input materials in Table 1 (a), needs to be fed into Pre-sorting. GHG emissions of this technology at 1,000 kg production scale are shown in Figure 2.



(a) By stage (b) By materials

Figure 2. GHG emissions by three-way sorting.

Total GHG emissions by three-way sorting to reclaim 1 kg of wrought aluminum is 0.168 kg-CO_2 eq/kg. The breakdown by stage is 0.095 kg-CO_2 eq/kg by Pre-sorting, 0.063 kg-CO_2 eq/kg by ECS sorting, and 0.010 kg-CO_2 eq/kg by LIBS sorting. GHG emissions by Pre-sorting are the highest. The biggest factor is the equipment, 0.0543 kg-CO_2 eq/kg. The reason for this is that the time duration of Pre-sorting process is long, 1.4 hour and its equipment cost is high compared with ECS and LIBS sorting. GHG emissions by equipment are the function of cost, processing time, and processing amount. With higher equipment cost and longer processing time, GHG emissions by Pre-sorting equipment became high. Another significant factor is GHG emissions by ECS sorting electricity. It is 0.0500 kg-CO_2 eq/kg. GHG emissions by electricity are the function of power requirement, processing time, and processing amount. ECS sorting equipment requires 5.4 kW, while that of Pre-sorting requires only 1.4 kW. For a given amount of processing amount, equipment requiring higher electricity emits more GHG emissions. GHG emissions by LIBS sorting are small. GHG emissions by electricity are 0.0040 kg-CO_2 eq/kg. The power requirement of LIBS sorting equipment is the largest among three processing equipment. However, its processing time is only 0.28 hours. Also, its processing capacity is 360 kg.

With a bigger capacity and short processing time, the amount of GHG emissions by LIBS sorting became small.

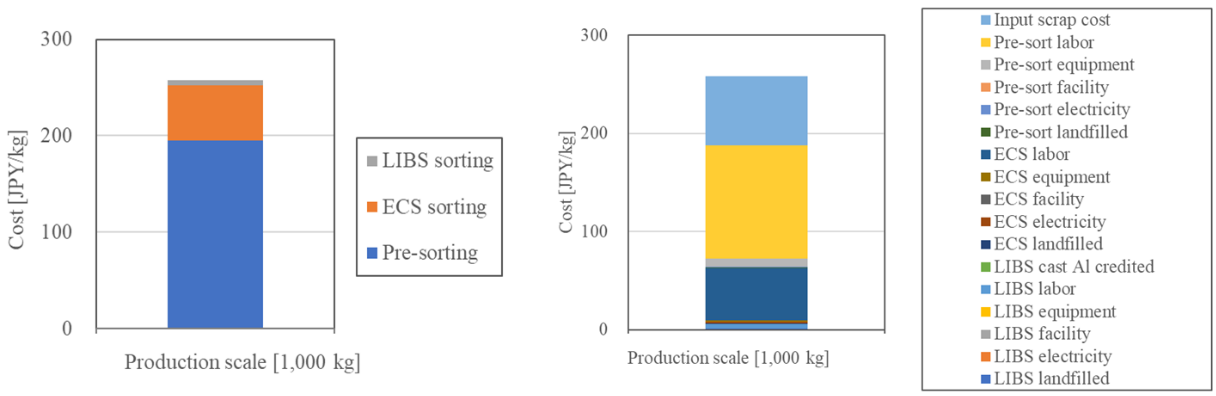
3.2. Cost analysis

The cost estimation includes input material cost, equipment cost, energy cost, facility cost, labor, and waste management. The cost for each item is shown in Table 3.

Table 3. Cost of each item.

Cost item	Amount	Unit
Input scrap	71	JPY/kg
Labor	3,500	JPY/hour
Electricity	18	JPY/kWh
Landfill	13	JPY/kg
Facility	3,000	JPY/m^2/month
LIBS credit (cast aluminum)	-100	JPY/kg

Detailed costs are obtained from the experts in the aluminum industry. As in the case of GHG emissions, cast aluminum obtained from LIBS sorting is not credited. Producing 1 kg of reclaimed wrought aluminum from scrap costs 259 JPY/kg. The cost is shown in Figure 3.



(a) by stage (b) by materials

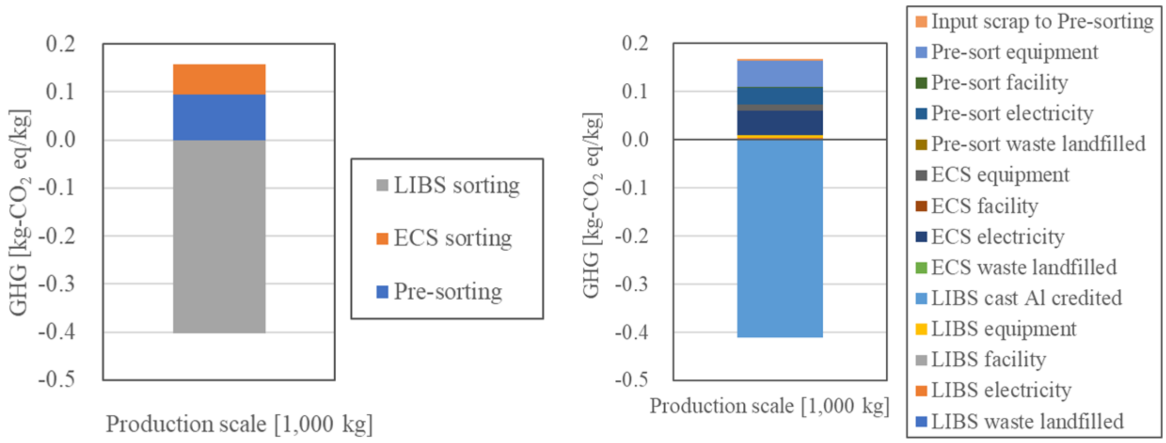
Figure 3. Cost of producing reclaimed wrought aluminum.

The biggest cost factor is labor, which constitutes 67% of the cost. Therefore, reducing labor cost is an effective way to lower the overall cost of this sorting technology. Among three sorting technologies, the cost of labor in Pre-sorting is the biggest one, 115 JPY/kg followed by ECS sorting, 53 JPY/kg. In Pre-sorting, it takes 1.4 hours, which is longer than ECS sorting (0.65 hour) and LIBS sorting (0.28 hours). Though the cost of screening 1 kg of wrought aluminum is 259 JPY/kg, the cost of input scrap is 71 JPY/kg. Therefore, the net cost of this screening technology is 188 JPY/kg.

4. Discussion

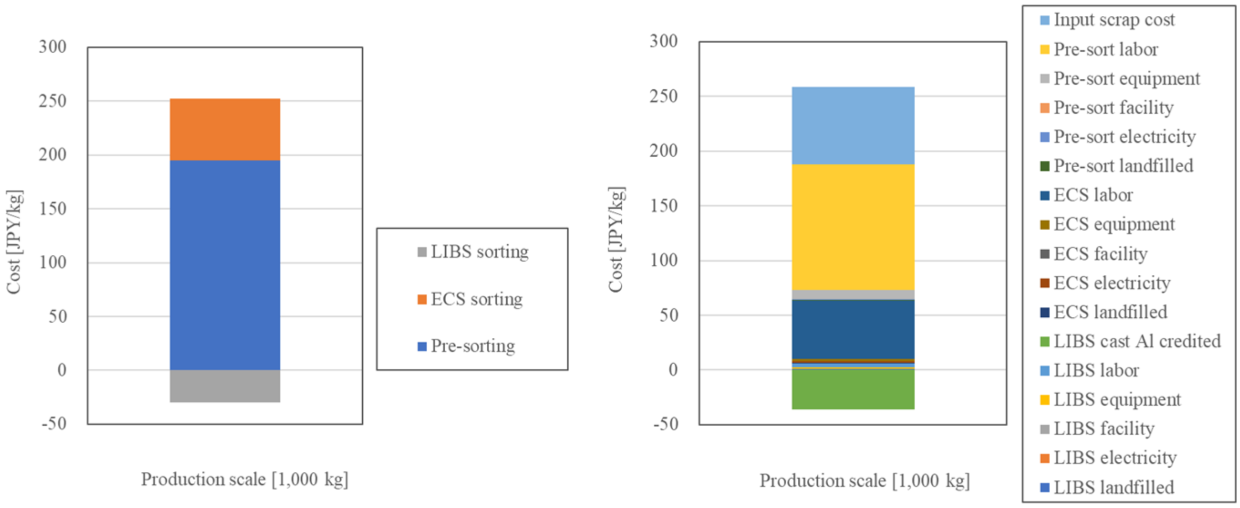
4.1. GHG emissions and cost analysis with credit

In the previous section, cast aluminum from LIBS sorting was not recycled and not credited. Now, let us consider a "what-if" scenario where the sorted cast aluminum can be used as cast aluminum. GHG emissions for this scenario are shown in Figure 4.



(a) GHG by stage (b) GHG by materials

Figure 4. GHG emissions with credit in consideration at a 1,000 kg production scale.



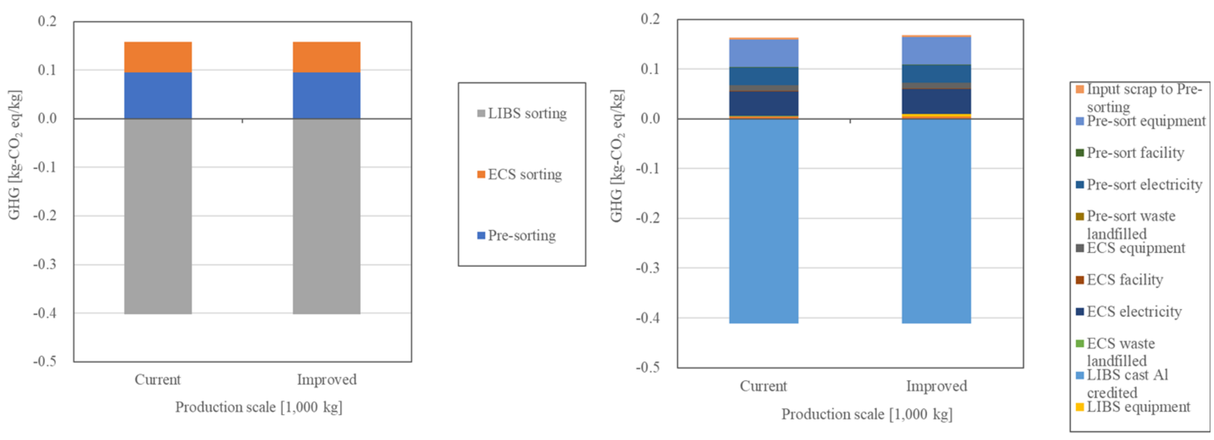
(a) By stage (b) By materials

Figure 5. Cost analysis with credit in consideration at 1,000 kg production scale.

In a "what-if" scenario where cast aluminum from LIBS sorting is used as cast aluminum, GHG credit for cast aluminum is constant at −0.411 kg-CO_2 eq/kg, denoted as “LIBS cast Al credited” in Figure 4 (b). The negative GHG emissions occur because this cast aluminum is generated from almost zero emissions scrap and used as secondary aluminum. According to the IDEA_v2.1.3 database, the GHG coefficient of secondary aluminum is 1.150 kg-CO_2 eq/kg. The total GHG emissions in this scenario are −0.243 kg-CO_2 eq/kg. This indicates that reusing cast aluminum from LIBS sorting with proper treatments can significantly reduce the total environmental burden. Similarly, the cost is estimated assuming cast aluminum waste is sold to the market. The resale price of cast aluminum is 100 JPY/kg, a value obtained from the Japan Aluminum Association (JAA) in March 2020. With the resale value credited, the total cost of producing 1 kg of wrought aluminum is 223 JPY/kg. The resale credit of cast aluminum is 36 JPY/kg. The cost breakdown by stage and materials is shown in Figure 5.

4.2.Consideration under an improved scenario

In mass production processes, labor force is often reduced as the system is designed to be more efficient with an automated operation. In this analysis, the production scale of 1,000 kg is chosen as it is considered a mass production scale. According to the National Institute of Advanced Industrial Science and Technology (AIST), labor can be reduced from 1 person per piece of equipment in Pre-sorting, ECS sorting, and LIBS sorting to 0.33 per piece of equipment. An operator has to attend the machine and watch the process all the time on a lab scale. However, on a mass production scale, the operator sets up and starts the machine and shuts down the machine at the end of the process. Occasionally, the operator checks its operation. This is the reason why labor can be reduced to 0.33 per piece of equipment. GHG emissions and their cost are calculated at 1,000 kg production scale. "Current" represents the current scenario with 1 person per piece of equipment. "Improved" represents the improved scenario with 0.33 person per piece of equipment. GHG emissions and their cost for the current and improved scenarios are shown in Figure 6 and 7. Cast aluminum obtained from LIBS sorting is credited in these calculations.



(a) By stage (b) By materials

Figure 6. Comparison between the current and improved scenarios in GHG emissions.

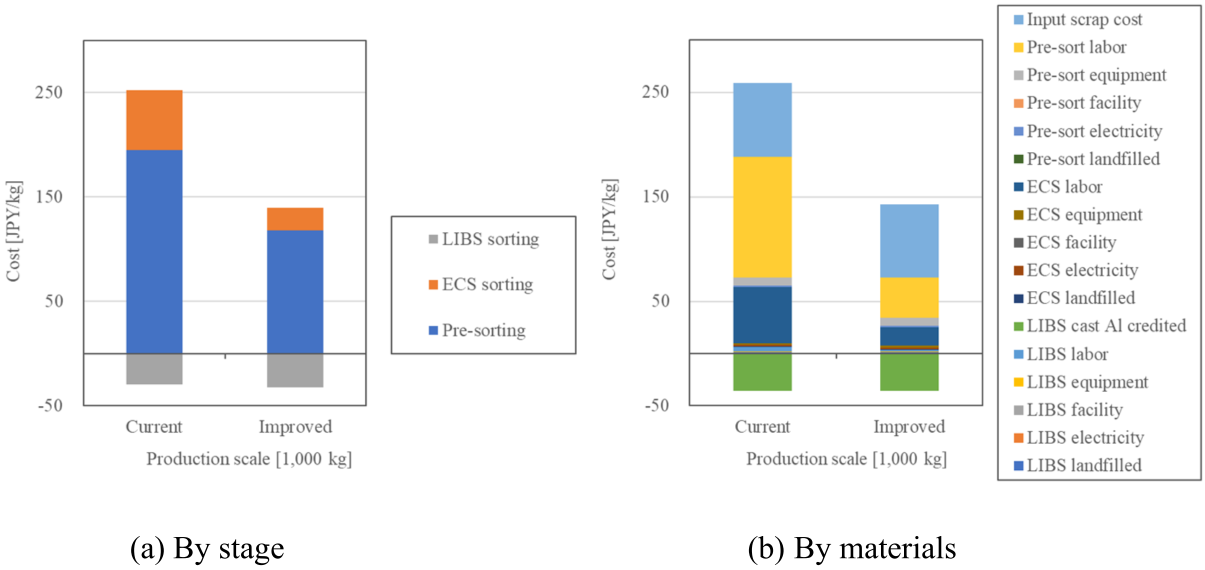


Figure 7. Comparison between the current and improved scenarios in cost.

GHG emissions of the improved scenario do not change from the current scenario because labor does not affect GHG emissions. However, it has a significant impact on the cost structure. The cost to produce 1,000 kg of reclaimed wrought aluminum was 223 JPY/kg with the current scenario, and it is reduced to 107 JPY/kg with the improved scenario which included the credit of cast aluminum from LIBS sorting. At a 1,000 kg production scale with the improved scenario, this technology becomes cost-effective in producing reclaimed wrought aluminum. The purchasing price of new A5052 aluminum is around 2,000 JPY/kg. Therefore, with proper management to achieve the quality of new wrought aluminum, the three-way sorting process becomes very attractive and competitive from environmental burdens and cost aspects.

4.3.Sensitivity analysis

To assess the influence of each input, a sensitivity analysis is conducted by changing each input parameter by plus and minus 10 % from the original input parameters. The result of the sensitivity analysis in GHG emissions and the cost of producing 1 kg of wrought aluminum are shown in Figure 8 and 9.

The sensitivity analysis showed that GHG emissions are heavily dependent on Pre-sort equipment and ECS electricity. They are followed by Pre-sort electricity. In Pre-sorting, the equipment has a larger influence than electricity. On the other hand, electricity has a larger influence than the equipment in ECS sorting. Therefore, this sensitivity analysis reveals that we should choose the lower cost equipment in Pre-sorting and high energy efficient equipment in ECS sorting at the expense of its cost. GHG emissions in other categories are barely changed. The cost of screening 1 kg of wrought aluminum was most dependent on Input scrap Aluminum cost and labor cost. This tells us that very little can be done in the cost as the input scrap and labor cost are out of our control. A possible area of reducing labor cost is to reduce a manpower in each sorting process as analyzed in the section, “4.2 The improved scenario.”

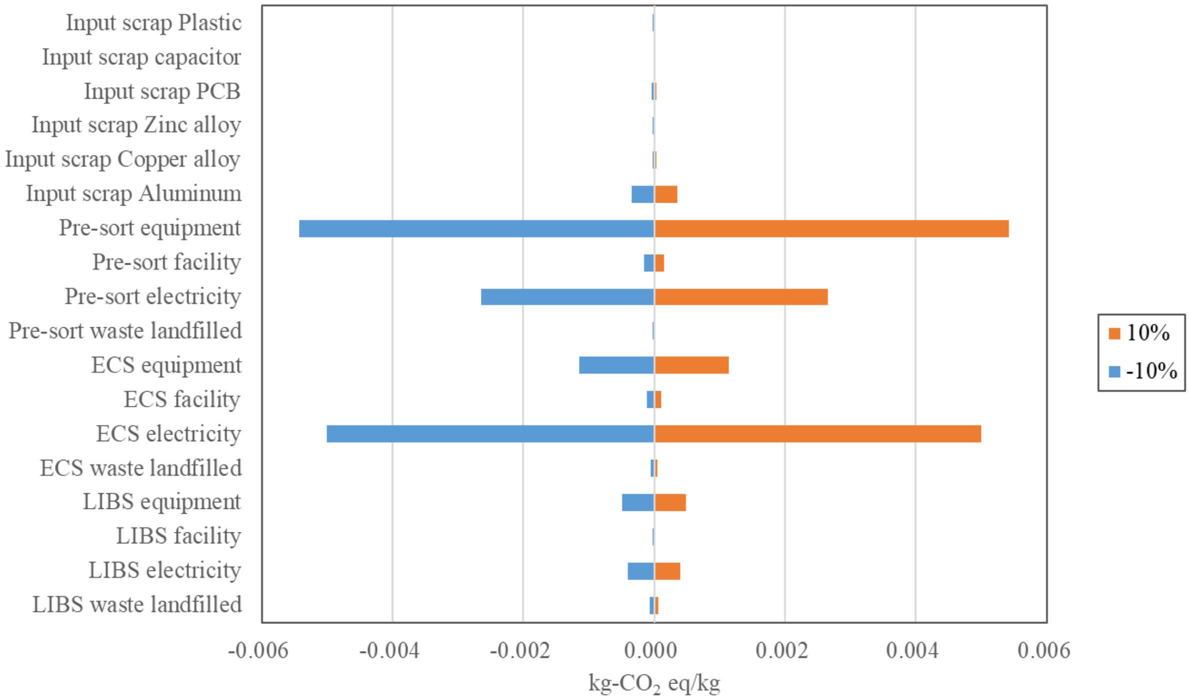


Figure 8. Impacts on GHG emissions by the input parameter change by 10%.

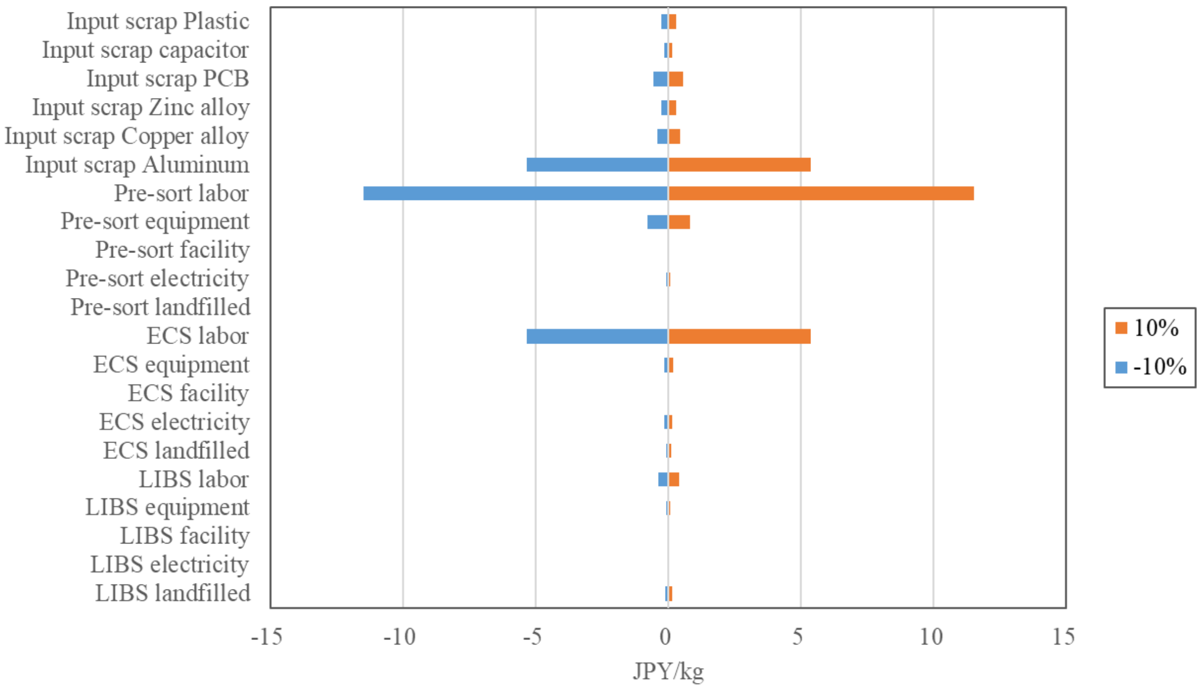
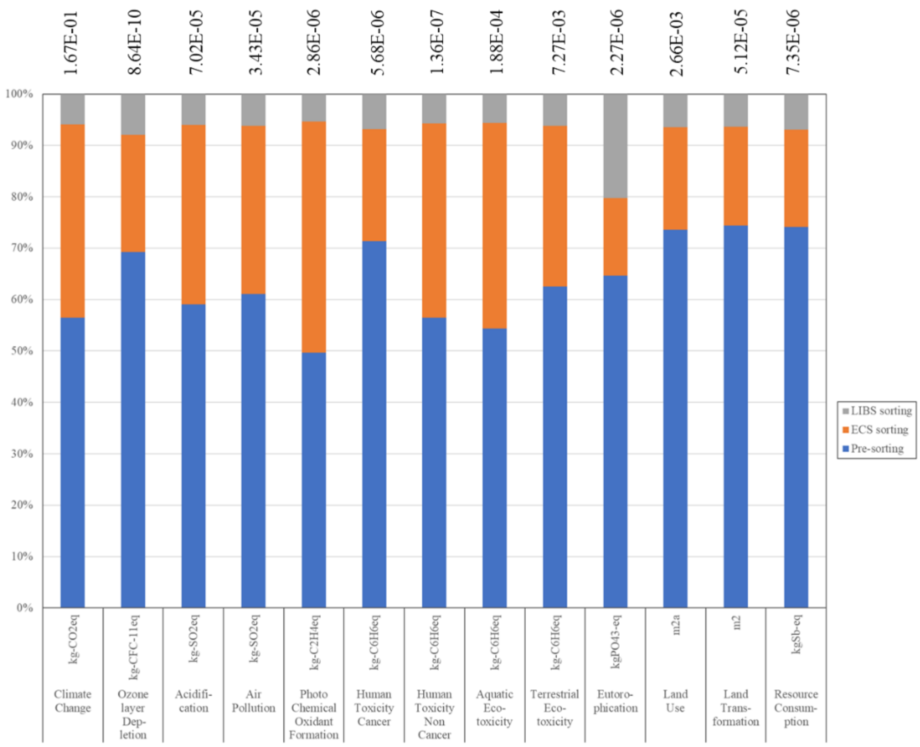


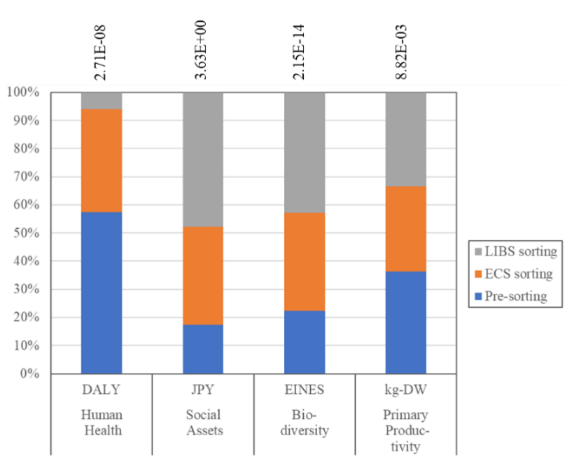
Figure 9. Impacts on the cost by the input parameters change by 10%.

4.4. Impact assessment

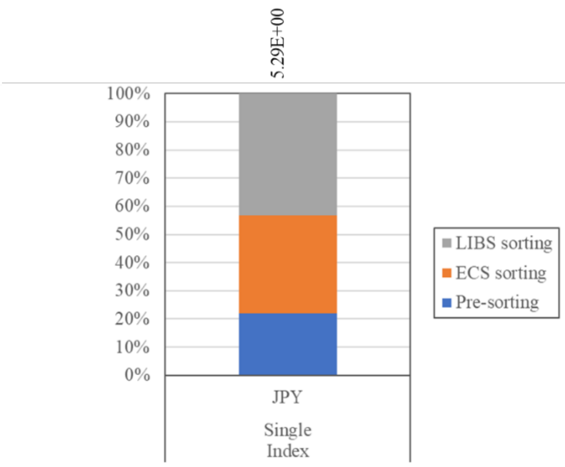
In order to assess the environmental impact more thoroughly, the impact assessment is conducted based on the LIME2 database, which is a part of the IDEA database. The result is shown in Figure 10. The stacked bar chart is used to show influences of each sorting process. The numbers on the chart are the numerical results of each category.



a) Impact analysis



b) Damage index



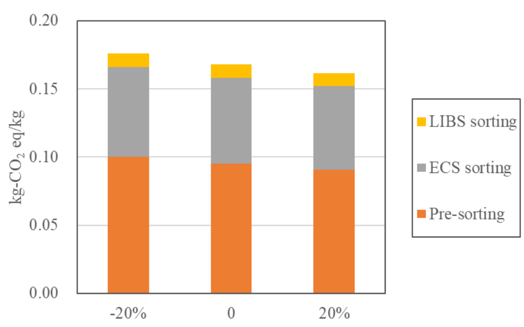
c) Single index

Figure 10. Impact assessment of three-way sorting.

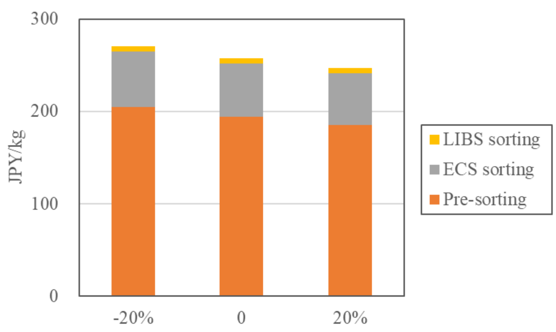
The impact assessment indicates that Climate Change (GHG) is the largest with 1.67E-01 kg-CO_2 eq/kg. Other categories that have large impacts are Aquatic Eco-toxicity (1.88E-04 kg-C_6H_6 eq/kg), Terrestrial Eco-toxicity (7.27E-03 kg-C_6H_6 eq/kg), and Land Use (2.66E-03 m^2a). Other than those categories, the rest are all below the digit of E-05 or below. Pre-sorting occupies more than 50% in all impact categories. As the case of Climate Change (GHG), the equipment and its electricity consumption contributes to larger amounts in each impact category. As for the Damage index, Social Assets score high number (3.6E+00). The rest of the three indices are small. The single index is 5.29E+00 JPY, which is considered very low. Therefore, three-way sorting technology is environmentally friendly.

4.5.Uncertainty analysis

The analysis is conducted based on the scrap mix in the inventory sheet. However, the content of scrap changes from time to time. Therefore, to assess GWP and its cost with different scrap mix, the analysis is conducted with the aluminum content plus and minus 20% in the original scrap mix. The rest of input materials amount are unchanged. GHG emissions and their cost due to aluminum content changes are shown in Figure 11.



(a) GHG emissions



(b) Cost

Figure 11. GHG emissions and their cost with aluminum content changes by plus and minus 20%.

The result shows that GHG emissions are 0.176 kg-CO_2 eq/kg when the aluminum content is reduced by 20% in the scrap mix and 0.162 kg-CO_2 eq/kg when the aluminum content is increased by 20% in the scrap mix. The GHG emission change rate has a 4.8% increase with 20% less aluminum content and a 3.7% decrease with 20% more aluminum content. The changes in GHG emissions are far less than that of the changes in aluminum content. The higher the aluminum content, the lesser the GHG emissions because the amount of final output, wrought aluminum, increases out of the input scrap. As for cost estimation, it is 271 JPY/kg with 20% less aluminum content and 247 JPY/kg with 20% more aluminum content. The cost change rate is a 5.1% increase with 20% less aluminum content and a 4.1% decrease with 20% more aluminum content. The rate of cost changes is far lower than aluminum content changes. The reason for this is the same as in the case of GHG emissions. This analysis suggests that input mix differences pose an insignificant effect on GHG emissions and the cost. Therefore, the analysis with the original input mix can be a good indicator to assess GHG emissions and the cost of the three-way sorting technology.

5. Limitation

The analysis conducted in this paper is based on data from AIST experts, and the allocation of input materials is based on their expert judgment, which may not reflect real scrap content. However, aluminum content in the scrap used in this paper is similar to Zorba Aluminium Scrap, which is commonly used scrap in aluminum recycling industry. Aluminum content of Zorba Aluminium Scrap is 70 to 90% [22]. While the input data used in this paper is based on the expert judgment, input data is not deviated so much compared with the industry standard scrap mix. Therefore, the results provide a good estimate for GHG and cost estimation of this technology and its performance for screening. In addition, wrought aluminum obtained by this technology requires further treatments such as rinsing and hot/cold treatments in order to be used as commercial grade wrought aluminum. It can be a future analysis topic to understand GHG emissions and the cost of three-way sorting technology.

6. Conclusions

GHG emissions and the cost for reclaiming wrought aluminum by three-way sorting were reviewed in this study. The following are the key findings from this study: GHG emissions for screening reclaimed wrought aluminum were 0.168 kg-CO_2 eq/kg. With the credit in case of cast aluminum was reused, it became −0.243 kg-CO_2 eq/kg. There is an effort to produce alloys with wrought aluminum properties from aluminum scrap with the fractional crystallization method [23]. GHG emissions by this technology are 1.20 kg-CO_2 eq/kg. Also, it is often mentioned that GHG emissions of recycled aluminum are 3% of primary aluminum [24]. Since GHG emissions of primary aluminum are 9.93 kg-CO_2 eq/kg [10], GHG emissions of recycled aluminum become 0.30 kg-CO_2 eq/kg. However, this recycling method used the remelting process, thus, the output was cast aluminum. In reality, in order to up-recycle from cast alloy to wrought aluminum alloys, dilution with primary aluminum is the most common solution used in industry today to reduce impurity content [25]. This indicates that producing wrought aluminum from remelting scrap results in much higher GHG emissions. Thus, three-way sorting is very environmentally friendly. The cost of screening reclaimed wrought aluminum was 259 JPY/kg, which was reduced to 223 JPY/kg with the credit. Under the improved scenario, the total cost decreased from 223 JPY/kg to 107 JPY/kg.

The sensitivity analysis showed that the lower cost equipment should be selected for Pre-sorting and energy efficient equipment should be selected for ECS sorting. On the other hand, there is little that can be done for the cost as the most impacted items, Input scrap Aluminum cost and labor, are out of our control. Additionally, an analysis was conducted to assess GHG emissions and their cost when aluminum content increased or decreased by 20% to understand the effects of scrap mix changes. In either case of increase or decrease of aluminum content by 20%, its impacts on GHG emissions and its associated cost were small. This suggests that analysis with the original scrap mix can be a good indicator in assessing GHG emissions and their cost. Impact analysis with the LIME2 database showed that three-way sorting technology was environmentally friendly.

GHG emissions by three-way sorting to reclaim wrought aluminum are far below those of primary aluminum of 9.930 kg-CO_2 eq/kg. Its cost is 223 JPY/kg, which is lower than the cost of A5052 aluminum at around 2000 JPY/kg. With the improved scenario, the cost can be further decreased to 107 JPY/kg, making it very competitive. However, as shown in the system boundary, subsequent treatments for reclaimed aluminum are necessary in order to use those reclaimed materials as commercial grade wrought aluminum. GHG emissions and its cost analysis, including subsequent treatment after three-way sorting, can be a future topic.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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