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Recyclability and Recoverability of Rolling Stock with Recycling Efficiency Factors

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ABSTRACT

To date, many studies focusing on recycling technologies, regulations and standards, material recovery, and environmental assessment of end-of-life products, end-of-life vehicles, and end-of-life ships have been conducted. In fact, the assessment of recyclability and recoverability for end-of-life products and vehicles is one of the most important issues in recycling and waste management. However, there is a lack of studies quantifying recyclability and recoverability at the end-of-life of rolling stock. Therefore, this study aimed to calculate their recyclability and recoverability taking into consideration the efficiencies of recycling and energy recovery processes. Experimental tests were conducted using a cone calorimeter and thermogravimetric analysis (TGA) for the energy recovery factor (ERF) values of four interior materials, which are not given. As a result, the end-of-life rolling stock revealed 84.8% recyclability and 88.3% recoverability by considering the recycling and recovery efficiencies. From this study, it was found that increasing and managing the efficiency of recycling process of materials are essential for better recyclability and recoverability of rolling stock. Attention is also needed when choosing the material recycling factor (MRF) and ERF of materials because the values can vary depending on the product type.

Keywords: end-of-life rolling stock, recyclability, recoverability, material recycling factor (MRF) and energy recovery factor (ERF), cone calorimeter

1. Introduction

It is well known that rail is the most environmentally friendly mode of transportation. It has greater safety and lower greenhouse gas emissions per person or unit of transported goods compared with road transportation. However, this may be limited to the operation stage because it is difficult to find appropriate answers to the question of whether railways still have better environmental performance at the end-of-life stage. In the past few decades, many studies involving directives and regulations have been conducted related to end-of-life vehicles (ELV), end-of-life ships (ELS), end-of-life products (ELP), and end-of-life renewable energy systems (Kanari et al, 2003; Go et al, 2011; Tian et al, 2014, Yee 2018; Gregsona et al, 2010; ABS, 2014; Hossain, 2015; Choi et al, 2016; Kim et al, 2009; Rahman et al. 2017; Imran et al., 2017; Bahers and Kim, 2018; Tazi et al. 2019; Cao et al. 2019; Hiratsuka et al. 2014; Lucas and Schwartze, 2001). These studies focused mainly on resource recoveries, material flows, evaluation of the environmental and economic impact of the recycling process, and policy aspects.

In 1997, the European Commission adopted a "Proposal for a Directive (Directive 2000/53/EC)" which aimed at making vehicle dismantling and recycling more environmentally friendly; set clear quantified targets for the reuse, recycling, and recovery of vehicles and their components; and pushed producers to manufacture new automobile vehicles that incorporated an ability to be recycled. In the European Commission (Directive 2017/2096/EC), the recycling regulation target value was set to 85 wt% in 2006 and 95 wt% in 2015. Therefore, the current vehicle industry and end-of-life treatment sectors are now paying attention to the recycling targets. Also, a series of studies on the application of eco-design to the transportation industry has been conducted since the ELV directives became effective.

Related to ELS recycling, the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (or Hong Kong Convention) was adopted in 2009. This convention was designed with the aim of improving health and safety related to current shipbreaking practices. This standard is for recycling practices that aim to minimize the negative effects of shipbreaking on the welfare of workers and the environment.

Similar to the Hong Kong Convention, EU regulations on ship recycling also entered into force on December 30, 2013 (European Commission, 2009, 2013; ABS, 2014). Under the Basel Convention of 2003 (UNEP, 2003), the recycling of ships using standard shipbreaking methods should be done in accordance with the technical guidelines for environmentally sound management.

Choi et al. (2016) analyzed the economic and environmental impact in three end-of-life ship management options, including a cost–benefit analysis and an environmental life-cycle assessment. The results showed that the economic aspects of end-of-life ship recycling depend on "the market price of reclaimed materials, ship purchase price, environmental and work safety regulation fees, labor costs, and overhead costs". Currently, standard end-of-life ship recycling methods are used in China, the European Union, the United States, and Turkey. Through this study, the standard method of end-of-life ship recycling and many life-cycle environmental benefits can be provided. One report by the NGO Shipbreaking Platform (2017) provided us with an overview of the problems related to dangerous and non-standard end-of-life ship recycling, as well as the challenges of finding sustainable solutions for clean and safe end-of-life ship recycling.

The railway industry has also implemented some projects to develop supporting tools for design-for-environment and eco-efficiency, as well as the life-cycle cost in rolling stock (Dewulf et al., 2001). Project PROSPER–Harmonized Environmental Specifications for New Rolling Stock, which was funded by the International Union of Railways (UIC), delivered UIC leaflet 345 “Environmental Specifications for New Rolling Stock” to assist railways in setting up environmental requirements and evaluating tenders in respect of environmental aspects: energy efficiency, noise, emitted pollutions, waste, materials, and recycling. As a result, a growing number of environmental product declaration (EPD) reports by European manufacturers have been published for newly made rolling stock, which cover quantified life-cycle environmental performance, including recyclability according to the Product Category Rules for Rail Vehicles and ISO 22628 (2002).

With respect to the calculation of recyclability and recoverability, defined as the ability of component parts, materials, or both to be diverted from an end-of-life stream to be recycled or recovered, for end-of-life rolling stock (ELRS), ISO 22628, which provides general procedures for measurement based on mass fraction for road vehicles, and the Union des Industries Ferroviaires Européennes (UNIFE), which was developed further in order to take into account the recycling efficiency based on ISO 22628, are currently available. Following these standards and guidelines, some studies have addressed the calculation results through case studies.

Huttunen M. and Trolin K. (2009) reviewed ISO 22628 and studied the recyclability and recoverability of an end-of-life train. The results show that about 99% of the materials used were considered recoverable (about 96% are recovered in practice today). Using the method of the ISO 22628 standard, a recoverability rate of just over 98% can be achieved. The authors clearly mention that application of the ISO 22628 standard for calculating the recyclability and recoverability of automotive vehicles to a commuter train is apparently possible.

The review study of Favoretto and Kaewunruen (2017) also provides a good summary of the recycling of rolling stock. They conducted an analysis of material components and mechanisms and reviewed the current state of practices for end-of-life rail vehicle procedures for passenger trains, high-speed trains, and freight trains. However, an assessment of recyclability and recoverability was not well conducted in this study.

When previous studies in the literature were examined, despite their significance, standards and regulations for ELVs, ELSs, and ELPs; evaluation tools; and empirical case studies on the recyclability, recoverability, and recycling/dismantling efficiencies of ELRSs have not been well studied or observed. We believe that it is necessary to conduct more studies on the assessment of recyclability and recoverability, as well as efficient factors. Consequently, the main purpose of this study was to establish a method for calculating the recyclability and recoverability of an ELRS along with the efficiency factor, material recycling factor (MRF), and energy recovery factor (ERF) of materials.

2. Recyclability and Recoverability

Recyclability rate embraces the percentage by design mass of the rolling stock that can potentially be reused and recycled, while the recoverability rate includes the percentage by design mass of the rolling stock that can potentially be reused, recycled and recovered as energy, as shown in Table 1.

Table 1. Concept of recyclability and recoverability (ISO 21106)

	Recovery			**Residue**
(Components) Reuse	(Materials) Recycling	(Materials) Energy recovery	(Materials) Disposal
Recyclability rate[a]			
Recoverability rate[a]			
Design mass of rolling stock			

[a] As a percentage of rolling stock mass.

ELRS must go through four steps (pretreatment, dismantling, metal separation/shredding, and shredder residue), according to ISO 22628 and the UNIFE guideline (2013), to enable recovery of as much of its constituent materials as possible and to minimize the overall environmental impact with fewer emissions of hazardous materials. The recyclability and recoverability of a vehicle by ISO 22628 (2012) are calculated by classifying its parts into seven categories (metals, polymers, elastomers, glass, fluids, modified organic natural materials (MONM), and others). After collecting all of the materials, the possibility of recycling and energy recovery at each step is determined using the following equations:

$$\mathbf{Recyclability} = \frac{m_P + m_D + m_M + m_{Tr}}{m_V} \times \mathbf{100} \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{Eq.\ (1)}$$

$$\mathbf{Recoverability} = \frac{m_P + m_D + m_M + m_{Tr} + m_{Te}}{m_V} \times \mathbf{100} \ldots\ldots\ldots\ldots \mathbf{Eq.\ (2)}$$

Here, m_V = vehicle mass [kg], m_P = mass of materials taken at the pretreatment step, m_D = mass of materials taken at the dismantling step, m_M = mass of materials taken at the metal separation step, m_{Tr} = mass of materials taken at the non-metallic residue treatment step for recycling, and m_{Te} = mass of materials taken at the non-metallic residue treatment step for energy recovery.

Despite ISO 22628 (2012), the UNIFE introduced MRFs and ERFs with equivalent factors for sixteen material categories, and placed importance on the dismantling process for higher recyclability.

There are three levels of recycling efficiency related to the process: the collection rate, the recycling process efficiency, and the element-specific recycling rate, which was considered in the Ueberschaar et al. (2017) study. The UNIFE defined recycling and recovery efficiency as the total mass (m) of material outputs from the recycling, either a reuse or a recovery process, divided by the input and taking into consideration the material losses during processing with two factors, MRF and ERF, as shown in the following equation:

$$\textbf{MRF and ERF} = \frac{\sum \boldsymbol{m_i(output)}}{\sum \boldsymbol{m_i(input)}} \times \mathbf{100\%} \text{ ....}\textbf{Eq. (3)}$$

Here, the input is the mass of the materials to be treated, and the output is the resulting mass of the recycling and energy recovery processes.

An important point to notice here is that the ERF is also a mass-based factor similar to the MRF, which means that the mass of materials, not the potential heat amounts, must be collected before and after the energy recovery process. For the ERF values of the materials for which generic data were not available, experiments using a cone calorimeter and thermogravimetric analysis (TGA) were implemented in this study.

No process can achieve 100% efficiency regarding the complete separation and recovery of materials because most products to be treated and residues from the previous end-of-life process are heterogeneous and unstable (Almeida and Borsato, 2019) and also the disassembly of ELPs containing a wide variety of materials combined with highly complex assemblies becomes complicated and expensive (Bakar and Rahimifard, 2008). Instead, to recover materials, many recyclers apply shredding processes in which the ELP waste is broken into small particles to release the materials (Favi et al., 2012). The reduction of automotive shredder residue is a key factor in maximizing the resource recovery rate and recycling efficiency (Chen et. al., 2010).

According to Bakar and Rahimifard (2008) and Favi et al. (2012), a higher efficiency of the shredding process, which is not considered for the calculation in the previous studies, is also a crucial factor for the recyclability and recoverability of rolling stock because rolling stock is also difficult to separate completely. In this regard, ISO 21106 introduced one more factor, the shredding loss factor (F_{SL}), to take into consideration the shredding process efficiency. Low F_{SL} values mean that fewer materials are sorted and will be later classified as residue.

$$m_{S,S} = \sum m_{S,i} \times (1 - F_{SL}) \text{ ....Eq. (4)}$$

Here,

$m_{S,S}$ = mass of materials available for the next process after the shredding stage

$m_{S,i}$ = mass of material i before the shredding process

This approach is different from that of the previous study, in which the dismantling of an ELRS was followed by the recycling processes described in ISO 22628 (2002) and UNIFE

(2013). The approach was used in order to determine the difficulties in recovering materials and identifying the kinds of limitations in applying the MRF and ERF of the UNIFE. It also demonstrated how many potential environmental benefits could be realized with a simple economic analysis.

3. Empirical Study

3.1 Dismantling an ELRS

In order to increase recyclability and recoverability, which are applied to the design stage as an indicator of predicting the potential of material recycling and energy recovery of the rolling stock being manufactured, it is important to analyze the current recycling status of the rolling stock to determine the chances of improving its recyclability and recoverability using commercially available recycling technologies.

The effectiveness of the dismantling process is directly related to the subsequent steps in the processing of various parts. The dismantling process can be classified into two modes: the European/American mode (Mayyas et al., 2012) and the Asian mode (Wang and Chen, 2013). Large-scale mechanized dismantling is commonly used in Europe and the United States due to the high cost of local labor. By contrast, “mechanical + manual” dismantling practices are commonly used in Asian countries due to the relatively low cost of local labor (Coates and Rahimifard, 2009). Most road ELVs are treated in specific workshops called authorized treatment facilities, which can manage waste treatment and storage (Simic, 2012; Simic, 2016a; Simic, 2016b). The ELRS are treated in the same workshops where repair and maintenance occurs, in dedicated plants, or in generic scrapyards (Delogu et al., 2017).

Japanese railways have a dedicated indoor facility that allows for the dismantling of railway rolling stock, the recovery of materials and components, and finally, the size reduction of car bodies by compression to fit into the shredding process. However, other countries, including Korea, do not have any similar facilities. This study performed dismantling in accordance with the ISO 21106 process, which is composed of three steps: pretreatment, dismantling, and shredding, on an ELRS (one passenger cabin of a high-speed car purchased from an operation company). As shown in the figure 1, it was transported to a yard where the dismantling proceeded with the weighing of each recovered material and part. As specified in ISO 21106, materials, parts, and substances were recovered at each recycling step to minimize secondary contamination throughout the recycling process. A checklist was used for the three stages (pretreatment, dismantling, and shredding), and the weight of each of the material and part was measured for the calculation.

Figure 1 shows the pretreatment and dismantling steps of the ELRS. First, all liquids (e.g., grease, water) and gases (e.g., coolant) are removed using dedicated technologies to avoid leakage. Then, the interiors and parts are separated in the dismantling process. In this step, it is very important to recover as many materials and parts as possible to achieve a higher recycling efficiency and reduce the economic cost. To analyze the current recycling status and compare the recycling results with recyclability, all materials and parts recovered during the process are weighed. In this study, the dismantling process was conducted manually so that the input labor was also measured as part of the economic feasibility study of the recycling process.

Fig. 1. Pretreatment and dismantling steps of ELRS
(One of the authors took the photos)

3.2 ERF with cone calorimeter and TGA experiments

With four interior materials that are currently used in rolling stock (interior panels, seat cushion foam, insulation, and flooring sheets), experimental tests for the ERF value were conducted under the following conditions:

- A cone calorimeter (Fire Testing Technology Ltd., UK) was used at an incident heat flux of 50 kW/m^2 in an air atmosphere, under free convective air flow conditions, to expose 100 × 100 mm samples in accordance to ISO 5660 (2015).

  Cone calorimeter has been widely used for the fire resistant test of each materials used into rolling stock throughout measuring heat & smoke release rate and mass loss rate. All test results of cone calorimeter shall be provided when supplying new rolling stock according to the railway safety law in Korea. A result of mass loss rate of the sample was used in the study.

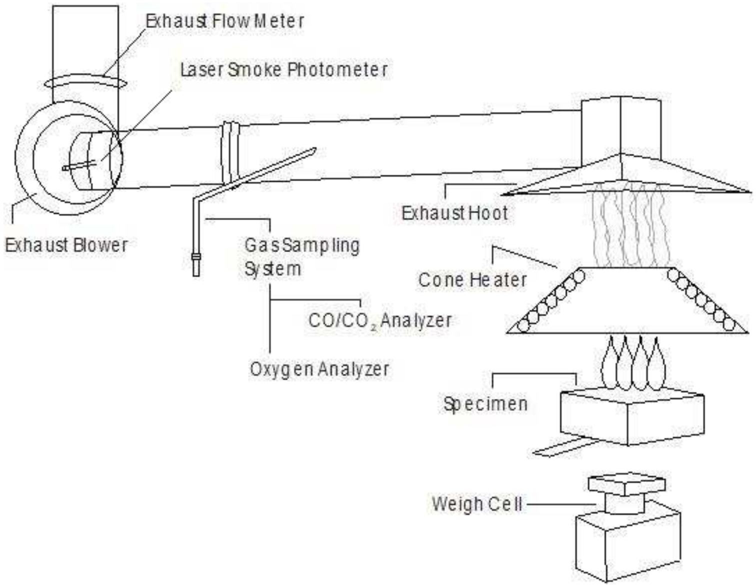

Fig. 2. Cone calorimeter

- TGA analysis: For the simultaneous differential thermal analysis (DTA)/TGA analysis, a thermogravimetric analyzer (STA 1500H, Rheometric Scientific) was used under flowing air (100 ml/min), at a heating rate of 5°C min^{-1}. About 10.0 mg of sample was used.

4. Results and Discussion

Rolling stock is made up of many heterogeneous components. In this regard, previous studies have proclaimed the important role of efficient recycling processes in ensuring the best use of resources at sustainable levels (Almeida and Borsato, 2019) and in achieving sustainability and a circular economy (Blomsma and Brennan, 2017; Bocken et al., 2017; Geissdoerfer, 2017; Kirchherr et al., 2017;).

In the railway industry, some studies that describe the current status of recyclability issues related to rolling stock with or without considering efficiency can also be found. Most studies (Merkisz–Guranowska, 2014; Delogu et al., 2017; Kaewunruen et al., 2019) take into consideration the efficiency-related factors provided by the UNIFE, which are from the manufacturer's viewpoint. On the other hand, Matsuoka et al. conducted field tests of two different recycling approaches (shredding before separation and shredding after separation) with various types of materials used in rolling stock car bodies (mild steel, stainless steel, and aluminum) to determine the recyclability and compare the cost.

As the accuracy and reliability of MRF and ERF values can vary depending on the reclaiming and recycling actors, ISO 21106 sets limitations on the sources of the efficiency factors used in calculating recyclability and recoverability, which are some of the major indicators for delivering environmental performance in the EPD reports for newly manufactured rolling stock. Until now, however, most of the calculation results are based on the UNIFE factors. However, the sources of those factors are not sufficient to meet the recommendations of ISO 21106.

In this study, we calculated recyclability and recoverability using the ISO 21106 template with recycling and recovery factors from IEC 62635, which are somewhat biased toward the recycling industry side, as well as values from the experiments using a cone calorimeter and TGA.

Table 2 shows the results of the classification of materials from each part and component, along with their weights and the man-hours put into dismantling.

Table 2. Weights of material and parts of a railcar (unit: kg)

Materials & Parts		Seat & Table	Cabin Wall	Window Glass	Cabin Ceiling	Cabin Floor	Boarding Gate	Coupler	Floor	Connection Parts	Wiring	Car Body	Bogie	Total	Ratio (%)
Metal	Ferrous	359.6				1,023.5	464.9	1,122.2	2,241.4	66.1		1,335.0	9,105.8	15,718.5	42.42
	Stainless	290.0	389.4		118.0	118.0	295.0	59.0	428.3	168.1		59.0		1,924.8	5.19
	Aluminum								35.2			10,590.0		10,625.2	28.67
	Copper				76.1				187.6					263.7	0.71
	Copper wire										1,554.7			1,554.7	4.20
	Communication cable										12.1			12.1	0.03
Organic	Plastic	116.0					37.7		85.2					238.9	0.64
	PU foam	243.6										302.4		546.0	1.47

	PE foam			54.0										54.0	0.15
	Vinyl											4.5		4.5	0.01
	FRP		925.0		605.0				172.5			300.0		2,002.5	5.40
	Rubber		6.5			305.0	12.0							323.5	0.87
	Film in glass			8.5										8.5	0.02
Wood	Plywood, etc.	139.2				650.0								789.2	2.13
Fiber	Fabric, felt, etc.	10.0	123.6			94.0								227.6	0.61
Inorganic	Silicone		11.0									56.3		67.3	0.18
	Glass		253.9	661.6			39.8					11.4		966.7	2.61
	Glass wool		182.0		150.0									332.0	0.90
Electrical device	Motor								53.5					53.5	0.14
	Light				74.2									74.2	0.20
	Air conditioner								714.3					714.3	1.93
	Boiler								163.8					163.8	0.44
	Panel, PCBs						149.4							149.4	0.40
	Monitor				115.3									115.3	0.31
Other	Refrigerant								10.1					10.1	0.03
	Oil								115.8					115.8	0.31
Total		1,158.4	1,891.4	724.1	1,138.6	2,190.5	998.8	1,181.2	4,207.7	234.2	1,566.8	12,658.6	9,105.8	37,056.1	100.00
Labor (M/H)		12	16	6	8	16	16	2	32	8	12	32	20		

In terms of the weight ratio, metals, such as ferrous and nonferrous, were mostly from components, which were about 81.2% of the total weight of the ELRS, followed by organic materials, such as plastic, polyurethane foam and fiber-reinforced plastic (8.56%), electrical devices (3.42%), and wood (2.13%). From Table 2, it can be seen that the most labor-intensive dismantling processes were those for the floor, car body, and bogies, amounting to 32, 32, and 20 man-hours, respectively. These processes were required for the subsequent process (shredding). That is because the body of a railcar was too long to feed into the shredder without prior treatment.

As a result, it was realized that application of design for disassembly, which aims at improving the ease and speed of disassembly, acting on vehicle joining techniques and structures, is much more important for recovering materials and parts efficiently and for reducing material losses during dismantling. It was almost impossible to separate materials and parts owing to the many different types of joining technologies.

In Table 3, the ERF values of all of the tested materials are summarized, with average values of mass losses after combustion from the three-time tests. It was found that materials in the seat foam and flooring sheet showed higher ERF values owing to their combustibility characteristics.

Table 3. Results of cone calorimeter test

	Interior Panel (Composite)	Seat Foam (Elastomer)	Insulator (Glass, wool)	Flooring Sheet (Thermoplastic)
Initial mass	40.7	9.5	10.4	45.4
Mass loss	8.7	7.2	0.5	19.3
% (ERF)	21.4	75.8	4.8	42.5

The TGA test, which was conducted to compare the results of the cone calorimeter, for four different types of interior panels (phenolic composite panels), showed that ERF values could vary from around 20% to 35%, according to the panel types (laminated and sandwich types) even though the same resin was used.

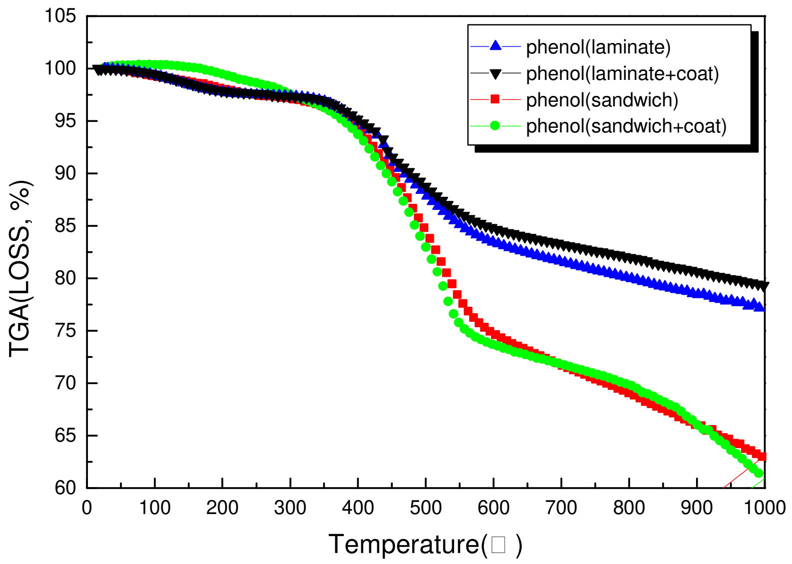

Fig. 3. TGA results of four different types of phenolic panel

In Table 4, the calculation results and findings are summarized. The distinctive findings from the field dismantling carried out on an ELRS are the following:

1) In this study, considering the efficiencies of material recycling and energy recovery, the overall recoverable material amounted to 88.3% with the remaining 11.7% destined to landfill. The results show that the EoL rolling stock had 84.8% recyclability and 88.3% recoverability. Table 4 shows additional details.

$$Recyclability = \frac{762 + 2{,}765 + 27{,}878}{37{,}056} = 84.8\ \%$$

$$Recoverability = 84.8\% + \frac{298 + 600 + 420}{37{,}056} = 88.3\ \%$$

2) This study applied efficiency factors from experiments with a cone calorimeter and from IEC 62635, which are somewhat biased toward the recycler as a result of the investigation of the MRF and ERF values for each material, followed by the recommendation of ISO 21106. It was found that it was not possible to use the MRF and ERF factors of the UNIFE without updates because some of them had lost the connection to their sources (e.g., rubber, plastics, and glass), and most of them are biased toward the manufacturer.
3) Attention must be paid when choosing ERF values of materials for the calculation of recyclability and recoverability of the intended rolling stock, in order to design for the purpose of manufacturing. That is because their values can be different according to the type of product even when the same materials are applied.

Table 4. Recyclability and recoverability of rolling stock

Material Category		Weight	MRF	ERF	Reuse	Recycling	Energy Recovery	Reuse	Recycling	Energy Recovery	Recycling	Energy Recovery	Residue
		(kg)	(%)	(%)	$m_{P,iReuse}$	$m_{P,iR}$	$m_{P,iE}$	$m_{D,iReuse}$	$m_{D,iR}$	$m_{D,iE}$	$m_{S,iR}$	$m_{S,iE}$	(kg)
Pretreatment	Electrics, electronics	957	79.0$^{1)}$	19.0$^{1)}$	0	756	182						19
	Oil, grease, or similar	116	0.0	100.0	0	0	116						0
	Acids, cooling agents, or similar	10	83.0	0.0	0	8	0						21.4
Dismantling	Metal (ferrous)	308	95.0	0.0					293	0			15
	Metal (nonferrous)	248	95.0	0.0					236	0			12
	Polymer (thermoplastics)	116	94.0	42.5*					109	49			42
	Composites	2,003	29.7	21.4*					595	429			979
	Electric and electronics	313	79.0	19.0					247	60			6
	Glass	1,299	74.0	4.8*					961	62			275
	Safety glass		74.0	0.0					0	0			0
	Mineral wool	244	75.0	0.0					183	0			61
	MONM	149	95.0	0.0					142	0			7
Shredding	Metal (ferrous)$^{2)}$	15,410.50	94.0	0.0							14,486	0	925
	Metal (nonferrous) $^{2)}$	14,132.50	93.0	0.0							13,143	0	989
	Elastomers$^{3)}$	324	14.2	24.0							46	78	200
	Polymer (thermosets)$^{3)}$	136	14.2	24.0							19	33	84
	Other inorganic materials (ceramics)	67	14.2	24.0							46.2	78.1	207.7
	Mineral wool	1,224	14.2	24.0							174	294	756
Sub-total (kg)		37,056 (100.0%)				765 (2.1%)	298 (0.8%)		2,765 (7.5%)	600 (1.6%)	27,878 (75.2%)	420 (1.1%)	4,331 (11.7%)

1) UNIFE (2013) ; 2) IEC (2012) ; 3) BMU (2012) ; * values are from the cone calorimeter

Table 4 shows the calculation results of recyclability and recoverability for pieces of rolling stock in South Korea. The recoverability of the ELRS was revealed at 88.3%, with consideration of recycling and recovery efficiencies. In this study, it was assumed that all shredded materials were sorted throughout the shredding process, which means that the shredding loss factor was not considered.

6. Conclusion

With the application of recycling and recovery efficiency factors that were biased toward the recycler to the calculation of recyclability and recoverability of rolling stock, it was revealed that the results were lower than the average values of the EPD reports by the UNIFE.

To deliver accurate environmental performance to customers, given the intention of the EPD reports, it is recommended that the MRF/ERF be used, as they represent state-of-the art knowledge. Given the MRF/ERF, generic values should be relevant regarding the practices of the reclamation and recycling industries. The values should also be economically feasible and not at the laboratory scale. This means that generic values should be based on reliable data, including official documents or statistics at the national level, at least.

In this regard, it is also very important that the manufacturer communicate with the recycler. This is because the manufacturer chooses to identify parts based on the recycler's feedback on critical issues affecting material separation, such as difficulty in shredding; material mixing incompatibility, which impairs recycling performance; and dismantling costs.

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Graphical abstract

Pretreatment and dismantling steps of End of Life Rolling Stock (ELRS)