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# Recyclability and Recoverability of Rolling Stock with Recycling Efficiency Factors

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31 interior materials, which are not given. As a result, the end-of-life rolling stock revealed 84.8%  
32 recyclability and 88.3% recoverability by considering the recycling and recovery efficiencies.  
33 From this study, it was found that increasing and managing the efficiency of recycling process  
34 of materials are essential for better recyclability and recoverability of rolling stock. Attention  
35 is also needed when choosing the material recycling factor (MRF) and ERF of materials  
36 because the values can vary depending on the product type.

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

39

## 40 **1. Introduction**

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

54 In 1997, the European Commission adopted a “Proposal for a Directive (Directive  
55 2000/53/EC)” which aimed at making vehicle dismantling and recycling more  
56 environmentally friendly; set clear quantified targets for the reuse, recycling, and recovery of  
57 vehicles and their components; and pushed producers to manufacture new automobile  
58 vehicles that incorporated an ability to be recycled. In the European Commission (Directive  
59 2017/2096/EC), the recycling regulation target value was set to 85 wt% in 2006 and 95 wt%  
60 in 2015. Therefore, the current vehicle industry and end-of-life treatment sectors are now  
61 paying attention to the recycling targets. Also, a series of studies on the application of eco-  
62 design to the transportation industry has been conducted since the ELV directives became  
63 effective.

64 Related to ELS recycling, the Hong Kong International Convention for the Safe and  
65 Environmentally Sound Recycling of Ships (or Hong Kong Convention) was adopted in  
66 2009. This convention was designed with the aim of improving health and safety related to  
67 current shipbreaking practices. This standard is for recycling practices that aim to minimize  
68 the negative effects of shipbreaking on the welfare of workers and the environment.

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

74 Choi et al. (2016) analyzed the economic and environmental impact in three end-of-  
75 life ship management options, including a cost–benefit analysis and an environmental life-  
76 cycle assessment. The results showed that the economic aspects of end-of-life ship recycling  
77 depend on “the market price of reclaimed materials, ship purchase price, environmental and  
78 work safety regulation fees, labor costs, and overhead costs”. Currently, standard end-of-life

79 ship recycling methods are used in China, the European Union, the United States, and  
80 Turkey. Through this study, the standard method of end-of-life ship recycling and many life-  
81 cycle environmental benefits can be provided. One report by the NGO Shipbreaking Platform  
82 (2017) provided us with an overview of the problems related to dangerous and non-standard  
83 end-of-life ship recycling, as well as the challenges of finding sustainable solutions for clean  
84 and safe end-of-life ship recycling.

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

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

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

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

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

124

## 125 **2. Recyclability and Recoverability**

126 **Recyclability rate embraces the percentage by design mass of the rolling stock that can**  
127 **potentially be reused and recycled, while the recoverability rate includes the percentage by**

128 design mass of the rolling stock that can potentially be reused, recycled and recovered as  
 129 energy, as shown in Table 1.

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

	Recovery		Residue
(Components) Reuse	(Materials) Recycling	(Materials) Energy recovery	(Materials) Disposal
Recyclability rate <sup>a</sup>			
Recoverability rate <sup>a</sup>			
Design mass of rolling stock			
<sup>a</sup> As a percentage of rolling stock mass.			

131  
 132 ELRS must go through four steps (pretreatment, dismantling, metal  
 133 separation/shredding, and shredder residue), according to ISO 22628 and the UNIFE  
 134 guideline (2013), to enable recovery of as much of its constituent materials as possible and to  
 135 minimize the overall environmental impact with fewer emissions of hazardous materials. The  
 136 recyclability and recoverability of a vehicle by ISO 22628 (2012) are calculated by classifying  
 137 its parts into seven categories (metals, polymers, elastomers, glass, fluids, modified organic  
 138 natural materials (MONM), and others). After collecting all of the materials, the possibility of  
 139 recycling and energy recovery at each step is determined using the following equations:

140  
 141 **Recyclability** =  $\frac{m_P+m_D+m_M+m_{Tr}}{m_V} \times 100 \dots\dots\dots \text{Eq. (1)}$

142  
 143 **Recoverability** =  $\frac{m_P+m_D+m_M+m_{Tr}+m_{Te}}{m_V} \times 100 \dots\dots\dots \text{Eq. (2)}$

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

150

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

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

160

161 
$$\text{MRF and ERF} = \frac{\sum m_i(\text{output})}{\sum m_i(\text{input})} \times 100\% \dots\dots\dots\text{Eq. (3)}$$

162

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

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

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

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

186

187 
$$m_{S,S} = \sum m_{S,i} \times (1 - F_{SL}) \dots\dots\dots\text{Eq. (4)}$$

188

189 Here,

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

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

192

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

195 (2013). The approach was used in order to determine the difficulties in recovering materials  
196 and identifying the kinds of limitations in applying the MRF and ERF of the UNIFE. It also  
197 demonstrated how many potential environmental benefits could be realized with a simple  
198 economic analysis.

199

### 200 **3. Empirical Study**

#### 201 **3.1 Dismantling an ELRS**

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

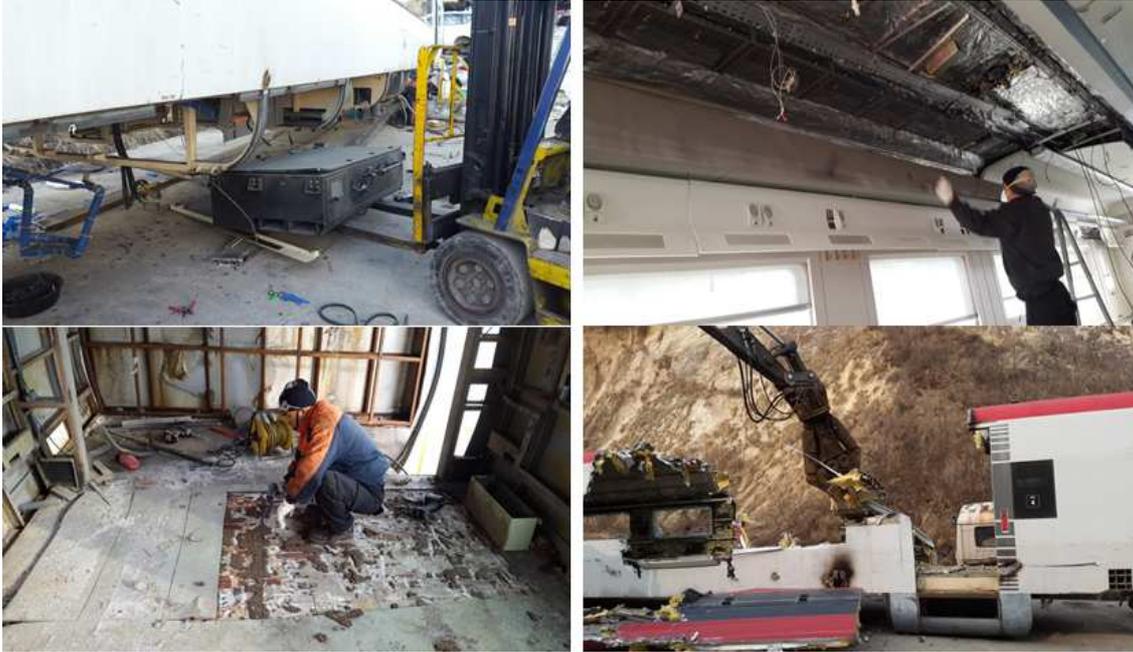
207 The effectiveness of the dismantling process is directly related to the subsequent steps  
208 in the processing of various parts. The dismantling process can be classified into two modes:  
209 the European/American mode (Mayyas et al., 2012) and the Asian mode (Wang and Chen,  
210 2013). Large-scale mechanized dismantling is commonly used in Europe and the United  
211 States due to the high cost of local labor. By contrast, “mechanical + manual” dismantling  
212 practices are commonly used in Asian countries due to the relatively low cost of local labor  
213 (Coates and Rahimifard, 2009). Most road ELVs are treated in specific workshops called  
214 authorized treatment facilities, which can manage waste treatment and storage (Simic, 2012;  
215 Simic, 2016a; Simic, 2016b). The ELRS are treated in the same workshops where repair and  
216 maintenance occurs, in dedicated plants, or in generic scrapyards (Delogu et al., 2017).

217 Japanese railways have a dedicated indoor facility that allows for the dismantling of  
218 railway rolling stock, the recovery of materials and components, and finally, the size  
219 reduction of car bodies by compression to fit into the shredding process. However, other

220 countries, including Korea, do not have any similar facilities. This study performed  
221 dismantling in accordance with the ISO 21106 process, which is composed of three steps:  
222 pretreatment, dismantling, and shredding, on an ELRS (one passenger cabin of a high-speed  
223 car purchased from an operation company). As shown in the figure 1, it was transported to a  
224 yard where the dismantling proceeded with the weighing of each recovered material and part.  
225 As specified in ISO 21106, materials, parts, and substances were recovered at each recycling  
226 step to minimize secondary contamination throughout the recycling process. A checklist was  
227 used for the three stages (pretreatment, dismantling, and shredding), and the weight of each of  
228 the material and part was measured for the calculation.

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

238



239

240

241

242

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

### 243 3.2 ERF with cone calorimeter and TGA experiments

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

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

250 **Cone calorimeter has been widely used for the fire resistant test of each materials used**  
251 **into rolling stock throughout measuring heat & smoke release rate and mass loss rate.**

252 **All test results of cone calorimeter shall be provided when supplying new rolling stock**  
253 **according to the railway safety law in Korea. A result of mass loss rate of the sample**  
254 **was used in the study.**

255

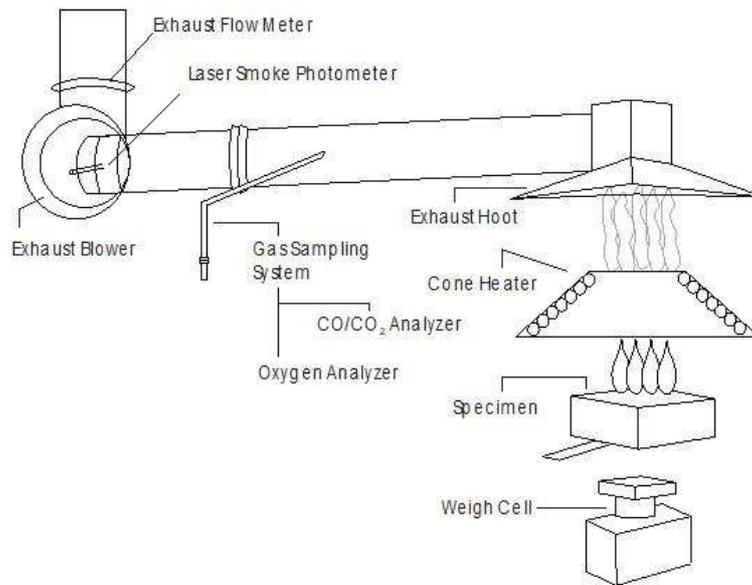


Fig. 2. Cone calorimeter

256

257

258

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

263

#### 264 4. Results and Discussion

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

270 In the railway industry, some studies that describe the current status of recyclability  
 271 issues related to rolling stock with or without considering efficiency can also be found. Most  
 272 studies (Merkisz–Guranowska, 2014; Delogu et al., 2017; Kaewunruen et al., 2019) take into  
 273 consideration the efficiency-related factors provided by the UNIFE, which are from the

274 manufacturer’s viewpoint. On the other hand, Matsuoka et al. conducted field tests of two  
 275 different recycling approaches (shredding before separation and shredding after separation)  
 276 with various types of materials used in rolling stock car bodies (mild steel, stainless steel, and  
 277 aluminum) to determine the recyclability and compare the cost.

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

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

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

291

292

**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		

293

294 In terms of the weight ratio, metals, such as ferrous and nonferrous, were mostly from  
295 components, which were about 81.2% of the total weight of the ELRS, followed by organic  
296 materials, such as plastic, polyurethane foam and fiber-reinforced plastic (8.56%), electrical  
297 devices (3.42%), and wood (2.13%). From Table 2, it can be seen that the most labor-  
298 intensive dismantling processes were those for the floor, car body, and bogies, amounting to  
299 32, 32, and 20 man-hours, respectively. These processes were required for the subsequent  
300 process (shredding). That is because the body of a railcar was too long to feed into the  
301 shredder without prior treatment.

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

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

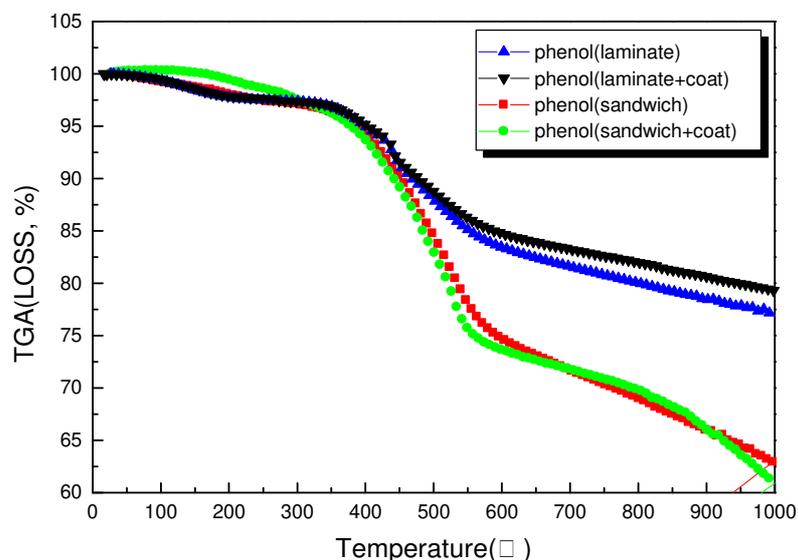
311

312 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

313

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



318

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

320

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

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

$$327 \quad \textit{Recyclability} = \frac{762 + 2,765 + 27,878}{37,056} = 84.8 \%$$

$$328 \quad \textit{Recoverability} = 84.8\% + \frac{298 + 600 + 420}{37,056} = 88.3 \%$$

329 2) This study applied efficiency factors from experiments with a cone calorimeter and  
330 from IEC 62635, which are somewhat biased toward the recycler as a result of the  
331 investigation of the MRF and ERF values for each material, followed by the  
332 recommendation of ISO 21106. It was found that it was not possible to use the MRF  
333 and ERF factors of the UNIFE without updates because some of them had lost the  
334 connection to their sources (e.g., rubber, plastics, and glass), and most of them are  
335 biased toward the manufacturer.

336 3) Attention must be paid when choosing ERF values of materials for the calculation of  
337 recyclability and recoverability of the intended rolling stock, in order to design for the  
338 purpose of manufacturing. That is because their values can be different according to  
339 the type of product even when the same materials are applied.

340

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)	(%)	(%)	<i>MP,iReuse</i>	<i>MP,iR</i>	<i>MP,iE</i>	<i>MD,iReuse</i>	<i>MD,iR</i>	<i>MD,iE</i>	<i>MS,iR</i>	<i>MS,iE</i>	(kg)
Pretreatment	Electrics, electronics	957	79.0 <sup>1)</sup>	19.0 <sup>1)</sup>	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) <sup>2)</sup>	15,410.50	94.0	0.0							14,486	0	925
	Metal (nonferrous) <sup>2)</sup>	14,132.50	93.0	0.0							13,143	0	989
	Elastomers <sup>3)</sup>	324	14.2	24.0							46	78	200
	Polymer (thermosets) <sup>3)</sup>	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%)

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

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

348

## 349 **6. Conclusion**

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

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

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

364

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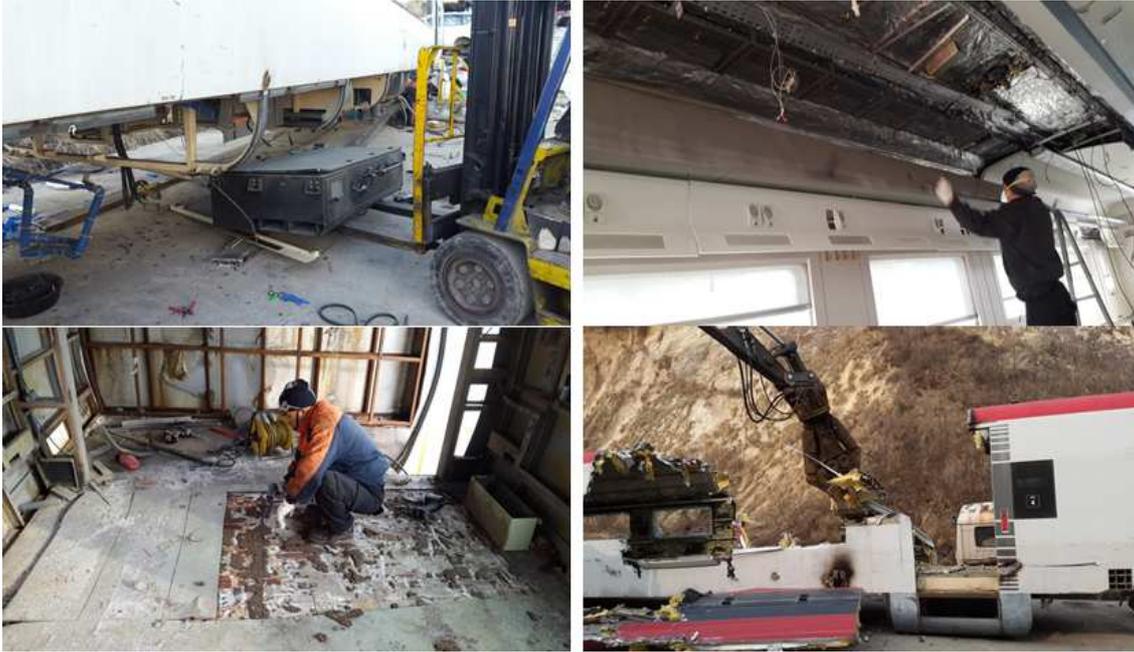
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## Graphical abstract



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