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Recycling and Material-Flow Analysis of End-of-Life Vehicles towards Resource Circulation in South Korea

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Abstract: The sustainable resource management of end-of-life vehicles (ELVs) towards a circular economy has become an issue of concern around the world. An understanding of recycling and the quantitative flow of ELVs is important because of their potential for resource recovery as well as the environmental impacts posed by their toxic chemicals upon disposal. In this paper, the generation and recycling system of ELVs in South Korea has been discussed based on a review of the available statistics and literature and site visits to ELV-recycling facilities. A material-flow analysis (MFA) for ELVs was performed to elucidate the resource recovery from recycling, while the substance flow of polybrominated diphenyl ethers (PBDEs) in automobile shredded residues (ASR) was also determined for proper management. Approximately one million tons of ELVs in 2020 were processed by dismantling and shredding treatment for the recovery of reusable and recyclable materials (803,000 tons), resulting in 78,300 tons of ASR. Approximately 97 tons of PBDEs as flame retardants were generated mainly from ASR in 2020 and processed via combustion, either with energy recovery (59.8%) or without heat recovery (39.2%). The monitoring of brominated dioxins and furans by unintentional release during the incineration processes of ASR is required in order to prevent the dispersion of the chemicals in the environment.

Keywords: end-of-life vehicles; recycling; material-flow analysis; polybrominated biphenyl ethers; automobile shredder residue

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Highlights:

(i) Material flow of ELVs was examined by life cycle.
(ii) Substantial amounts of PBDEs are often found in seat fabric and ASR.
(iii) Monitoring of PBDEs in ASR is required in order to reduce the dispersion in the environment.
(iv) Automobile producers should take more responsibility to meet the target recycling rate of 95%.

1. Introduction

In 2020, approximately 78 million new cars around the world were manufactured, and the annual production of automobiles was decreased by 15%, compared with the previous year, mainly due to the economic recession by COVID-19 [1]. According to the International Organization of Motor Vehicle Manufacturers (OICA), there were more than 1.28 billion vehicles in use in the world as of 2015 [2]. In 2040, it is expected that the fraction of electric cars (54%) among new cars to be sold in the world will be higher than that of internal combustion locomotives (46%). Additionally, by 2040 it is projected that more than 1.6 billion cars will be on the road globally and that 30% will be electric, hence conserving more than eight million barrels of oil [3]. In 2019, the number of passenger cars on the road in the European Union reached 243 million [4]. South Korea, one of the major automobile manufacturing countries in the world, produced approximately 3.5 million new vehicles for exports and domestic demands in 2020 [5]. As of 2020, the number of passenger vehicles registered in South Korea was about 24.4 million, compared to only 190,000 vehicles in 1975, while the use of electric cars in the country has rapidly grown from 60 in 2010 to 95,001 in 2019 [6].

The large consumer demands for new vehicles have resulted in tremendous amounts of end-of-life vehicles (ELVs) waiting for proper treatment. In addition, as new cars equipped with modern technology such as artificial intelligence, an autonomous system and electric batteries with energy savings are coming to the markets at a growing rate, the quantity of ELVs may be expected to increase [7,8]. In 2020, approximately 950,000 ELVs were generated in South Korea [6], while 3.7 million ELVs in 2017 in Japan [9] and 6.1 million in 2018 from 27 EU countries [10] were generated.

ELVs are typically composed of numerous materials with a range of 20,000 to 30,000 different parts, including ferrous and non-ferrous metals, plastics, rubber, glass, textiles, wires, and many other materials [11–13]. Some of the materials are valuable resources such as iron, copper, zinc, aluminum, lead, and platinum [14–16], although the material composition can vary depending on the type, size, manufacture year, and model of vehicle. The re-use of auto parts (glass, tires, engines, transmission, doors, seats, batteries) from ELVs is beneficial in terms of resource conservation as long as automobile safety is maintained. Thus, it is important for ELV dismantlers or disassemblers to obtain detailed material compositions for identifying reusable parts on the market before they proceed with the dismantling and shredding steps.

In addition to a large fraction of valuable resources, ELVs also contain toxic constituents (e.g., engine, brake and transmission oils, fuels, anti-freeze, refrigerants, brominated flame retardants, heavy metals, and lead-acid batteries) [8,13,17–19]. Such toxic materials can pose a potential hazard to human health and the environment if improperly handled or disposed of. For example, oil fluids remaining in ELVs can run off into surrounding soils or streams during disassembly if no appropriate measures are taken. Thus, any oils in ELVs should be properly drained before dismantling in order to prevent their dispersion into the environment. Refrigerants retained in ELVs such as R-134a and R-1234f can also become of significant concern due to potential emissions into the air. They are commonly known as greenhouse gases with relatively high global-warming potential (GWP) (R-134a as GWP 1370) [20]. Brominated flame retardants (e.g., polybrominated diphenyl ethers in seat fabric, floor covers, and automobile shredded residues) from plastic materials in ELVs can be emitted into the air during the dismantling and treatment stages. Although such chemical components may exist in only a small fraction of vehicles, they may account for a large amount of toxic chemicals if the total cumulative volume of ELV streams is considered. Thus, the environmentally sound management of ELVs with potentially toxic constituents is an issue of concern for solid-waste facilities.

In response to the growing concern over resource-recovery potentials and potential impacts, many developed countries have been trying to establish environmentally sound and economically feasible models for an ELV-recycling-and-management system. For example, some European countries have made efforts towards resource conservation and proper treatment by establishing the disassembly processes, shredding processes and residue treatment of ELVs with the concept of an extended-producer-responsibility (EPR) system. In early 2000, EU started the regulations by adopting Directive 2000/53/EC on end-of-life vehicles (EU ELV Directive) [21–23]. It requires the restricted use of toxic metals (e.g., lead, mercury, cadmium, hexavalent chromium) in vehicles in order to minimize the release of such pollutants into the environment as well as to facilitate dismantling and to allow for recovered materials to be re-used and recycled by the beginning of 2003. The directive also stipulated a recycling rate (re-use/recycling) of 80% and a recovery rate (re-use/recovery) of 85% by the beginning of 2006. Starting in 2015, the target rates were increased to 85% for recycling and 95% for recovery. Automobile manufacturers take responsibility for the reclamation of their vehicles sold on the market and are required to provide suitable collection systems to consumers for recycling.

In Japan, legislation on ELV recycling was implemented in 2005 based on the shared EPR concept. Automobile manufacturers including importers take responsibility for the collection and recycling of ELVs. An automobile-recycling network between stakeholders was established in order to properly manage and treat ELVs. When consumers buy a new car, they are required to pay a recycling deposit in the approximate range of $70 to $650, depending on the type and model of the car, in order to cover a portion of the recycling cost [7,9,24]. The manufacturers financially support the automobile-recycling industry in the treating of three main groups (i.e., refrigerants, airbags, and automobile shredded residues). Automobile manufacturers have voluntarily agreed to prohibit the use of four substances of concern in vehicles (lead, mercury, cadmium, and hexavalent chromium) in order to reduce their potential environmental impacts upon disposal. It should be noted that the Japan Automobile Manufacturers Association (JAMA) decided to voluntarily cease the use of hexabromocyclododecane (HBCD) in vehicles by the end of 2010 [19,25].

The current management options for ELVs include re-use, recycling, incineration, and landfilling. Among the options, re-use and recycling are the preferred methods, not only from a pollution-prevention perspective but also from a resource-recovery perspective. For the sustainable management of natural resources and the reduction of environmental impacts, as many valuable resources as possible (e.g., ferrous and non-ferrous metals and automobile catalysts) should be recovered from ELVs and recycled during the dismantling and shredding processes. Developed countries such as those in the EU, the USA, and Japan have been trying to establish an efficient recycling system for ELVs in order to recover valuable resources as well as to reduce their potential environmental impacts upon disposal [7,8,22]. A number of studies have been conducted to improve the management of ELV-recycling systems and processes [14–16,26–35]. In the EU, recycling trends and performances were assessed by a systematic overview. It predicted that the recycling rate can reach up to 89% by 2030 by enhanced resource-recovery practices towards a circular economy [33]. In China, it was estimated that more than 26 million passenger vehicles largely consisting of steel (19 million tons) and plastic materials (6 million tons) will be retired by 2030. By the recovery of recyclable resources, the value of the economic benefits can reach up to $14.4 billion in the year [35]. While the recycling statistics on ELVs are readily available, especially in the EU and Japan [19,36–40], there are still very limited studies regarding the levels of toxic substances in various waste materials and the quantitative flow of ELVs by dismantlement/disassembly, shredding, and final treatment stages in South Korea. Current efforts and perspectives on the recycling of end-of-life batteries from electric vehicles were discussed regarding the resource recovery of cobalt and lithium as well as the control of the toxic substances they contain (e.g., lead, cadmium, copper) [41]. The determination of the levels and flow of toxic substances in ELVs is very important in order to develop an appropriate waste-management policy for better recycling and treatment.

The aim of this paper is to present an overview of recycling practices and material flows of ELVs towards a circular economy in South Korea. More specifically, our study examined the generation, recycling practices for resource recovery, and treatment of ELVs. A material-flow analysis (MFA) for ELVs and the levels of polybrominated diphenyl ethers (PBDEs), among other potentially toxic substances in ELVs, were determined in order to provide their mass flows by life cycle. Finally, current issues and future challenges are presented for the environmentally sound and sustainable resource management of ELVs.

2. Methodology

2.1. Data Collection and Methods

The methodology employed in this study included sample collection from five ELV-shredding facilities, statistical data analysis associated with annual manufacturing, registration of automobiles, site visits to dismantling, shredding, and automobile-shredded-residue

(ASR)-treatment facilities with interviews and conversations, and a review of the available literature and relevant previous studies. Detailed data regarding domestic automobile manufacturing, the amount of automobile registration and deregistration, the amount of automobile imports and exports, domestic demands for automobiles, and recycling statistics were also obtained from the Korean Bureau of Statistics and the Korea Ministry of Environment (Korea MOE), and Korea Environment Cooperation (KECO). The KECO, a semi-governmental organization under the Korea MOE, operates the recycling system for ELVs, supports the ELV-recycling industry, and provides statistical data. Interviews and conversations with officials from the Korea MOE and KECO, experts from the ELV-recycling industry and academia were conducted in order to identify the details of the recent progress and development associated with ELV recycling and management.

2.2. Collection and Chemical Analysis of ELVs Samples

A total of 36 samples were collected from automobiles from dismantling facilities and ASR-processing facilities in 2017. In the previous study, a total of 128 samples were collected that comprised 92 components and 36 waste samples [42]. In this study, we mainly focused on the samples (e.g., ASR, seat fabrics, indoor lights, and ceiling and floor covers) that may contain high levels of BFRs. X-ray fluorescence (XRF, SEIKO 1200) was used in the pre-screening process to detect bromine in the plastic samples (e.g., dashboards, bumpers, door trims, floor fabric materials, indoor light covers, seat belts, fuel and oil hoses, seat fabrics, fuse container boxes, and polyurethane) that exceeded the limit of 0.01% or 100 mg/kg of bromine (by dry weight). Once the XRF samples exceeded the limit, they were quantitatively analyzed by Gas Chromatography Mass Spectrometry (GC/MS) equipment (Perkin Elmer Clarus 500) by following the IEC 62,321 method to identify polybrominated diphenyl ethers (PBDEs). The sample preparation, analytical methods and operating conditions were the same as the pervious study [42] and can be found there in more detailed description.

2.3. Material-Flow Analysis of ELVs

Material-flow analysis (MFA) quantifies the mass/resource flow and loss in a defined system and facilitates data reconciliation in a well-defined space and time. In this study, a MFA of ELVs and a substance-flow analysis (SFA) of PBDEs in ASR were performed by life cycle (i.e., production, use, generation, collection, recycling and disposal stages). The relevant data were collected and acquired according to the life cycle of the vehicles in order to conduct the MFA and SFA analysis, as shown in Table 1. Data with regard to the number of automobiles that are manufactured, exported, imported, registered and deregistered were collected from the Korea Statistical Information Service (KOSIS) and the Korea Trade Statistics Promotion Institute, while the recycled and disposal amounts of ELVs were obtained by the KECO under the Korea MOE. The average weight per vehicle for the MFA was assumed to be 1279 kg, which was provided by the KECO, although the weight of vehicles may vary depending on their type and model. The combined average concentrations of PBDEs in ASR from ELVs in this study and the previous study [42] were used for the SFA. The MFA software STAN (2.6.801) was employed to perform material-flow analysis in order to display the quantitative flow of ELVs [43,44].

Table 1. Data collection and acquisition for material-flow analysis for ELVs.

Life Cycle	Type of Data	References
Export/Import	Export/Import of automobiles	Korea Trade Statistics Promotion Institute, 2020
Manufacturing	Manufacturing of automobiles	Korea Statistical Information Service (KOSIS), 2020
	Domestic demands for automobiles	Korea Statistical Information Service (KOSIS), 2020
Use and generation	The number of automobiles registered	Korea Statistical Information Service (KOSIS), 2020
	The number of automobiles deregistered	Korea Statistical Information Service (KOSIS), 2020
	Used cars exported and imported	Korea Trade Statistics Promotion Institute, 2020
Recycling	Number of automobiles dismantled by recycling facilities	Korea Environment Cooperation
	Number of automobiles shredded by recycling facilities	Korea Environment Cooperation
	Amount of ASR treated by ASR-processing facilities	Korea Environment Cooperation
Disposal	Incinerated amount	Korea Environment Cooperation
	Landfilled amount	Korea Environment Cooperation

3. Results and Discussion

3.1. Management System of ELVs in South Korea

3.1.1. Regulations of ELV Management

In South Korea, ELVs have been managed by the Act on Resource Circulation of Electrical & Electronics and ELVs since 2008, which is similar to the EU WEEE and ELV Directive. It regulates the restricted use and prohibition of toxic substances (e.g., cadmium, hexavalent chromium, lead, and mercury) in vehicles and promotes their recycling by establishing a resource-circulation system of ELVs. It set a mandatory target recycling rate of 95% including 10% energy recovery as a maximum in the beginning of 2015 [45]. Before 2015, the target recycling rate was 85%, including a 5% energy-recovery rate as a maximum. Each stakeholder should play a role in the recycling and treatment of ELVs by following the obligations at each stage (collection, disassembly, shredding, and disposal) according to the ELV recycling and treatment standards set by the act. For example, the automobile-dismantling facilities should comply with the recycling methods and standards and transfer the non-reusable and recyclable materials from ELV disassembly to shredding facilities for further treatment and the refrigerants to waste-gas-treatment facilities.

3.1.2. Recycling Systems of ELVs in South Korea

Figure 1 displays the current recycling-and-management system of ELVs in South Korea. The several stakeholders (i.e., manufacturers and importers, dismantling facilities, shredding facilities, ASR-treatment facilities, and refrigerant-treatment facilities) involve the recycling-and-treatment system of ELVs. ELV transporters that are contracted with the dismantling facilities collect the vehicles from the owners with or without charging the treatment cost depending on their price on the market after deregistration in a local municipality. Automobile manufacturers and importers (or producers) that are contracted with the transporters are also required to collect ELVs from the owners without charge, often providing them with economic rewards based on the market price. The manufacturers and importers partially support the recycling system by covering the collection and recycling costs of ELVs, if the market price of the ELV is less than the collection and recycling cost. The transporters send them to designated automobile-dismantling facilities for manual and mechanical disassembly processes by reclaiming reusable and recyclable parts (e.g., engines, catalysts, airbags, tires, fuel tanks, bumpers, batteries and many others) as well as by recovering liquids and gases (e.g., motor oils, fuels, refrigerants) for proper treatment. After dismantling, the remaining fraction is processed in shredding facilities with screening, hammer mill, magnetic, optical, density, and manual separations to remove the ferrous and non-ferrous fractions. The final residue is known as automobile shredded residue (ASR), which is sent to the ASR-treatment facilities. The residue is estimated to be between 15%

and 40% of the total weight of ELVs, typically consisting of plastics, textiles, sponge, rubbers, metals, glasses, wires, and dirt [46,47]. The ASR facilities further process the residue by crushing, screening and various separations to recover the ferrous and non-ferrous metals (aluminum, copper, lead, and zinc), plastics, rubber and glass.

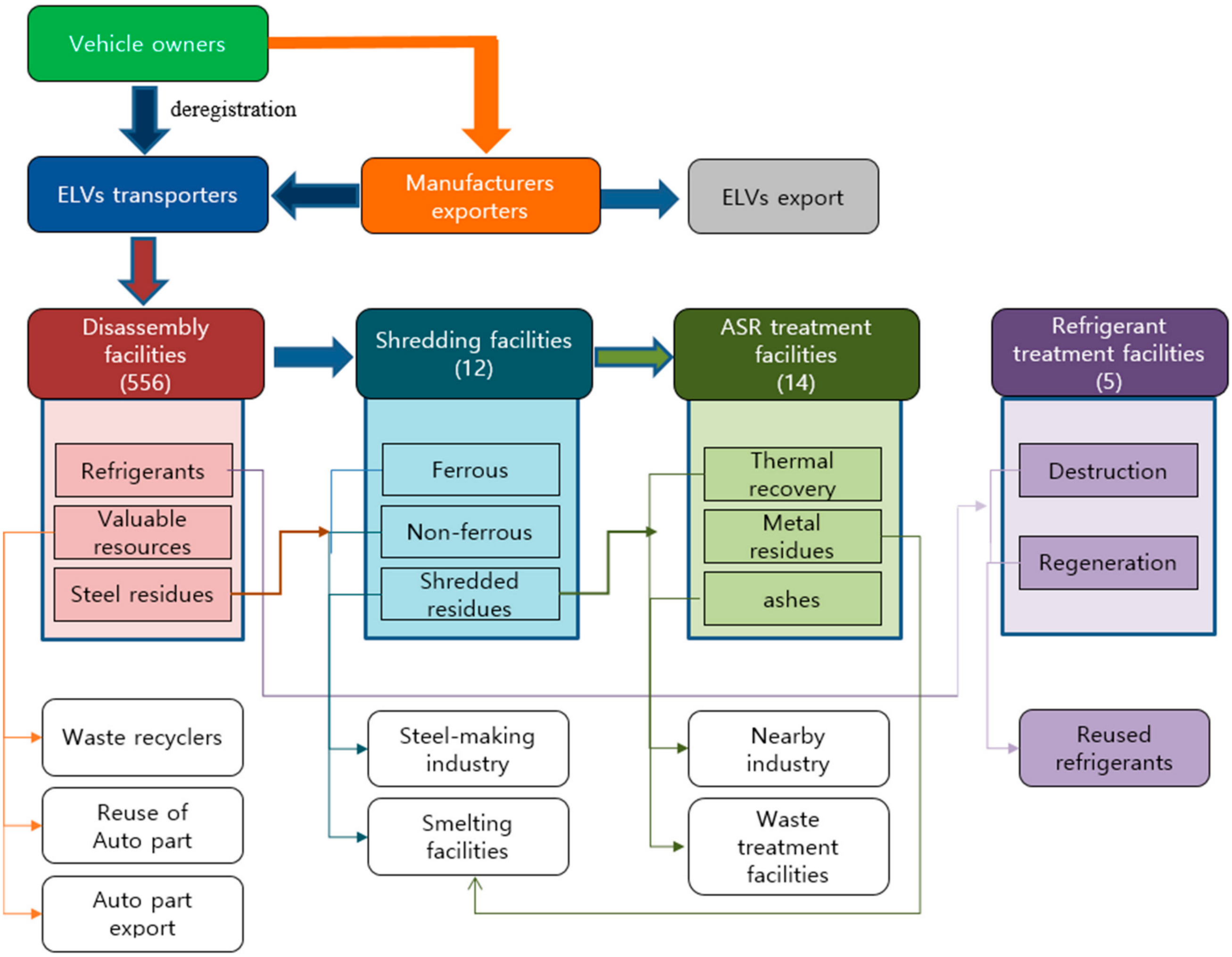

Figure 1. The recycling-and-management system of ELVs in South Korea [48].

3.1.3. Generation and Recycling Rates of ELVs

Table 2 presents the generation of ELVs and the number of dismantling facilities in South Korea. The generation rates over the past decade have been increasing from 611,565 ELVs with 417 dismantling facilities in 2008 to 862,606 ELVs with 556 dismantling facilities in 2020. Each dismantling facility processes approximately 1500 ELVs per year on average.

Table 2. Number of ELVs and disassembly facilities of ELVs in 2008 and 2020 in South Korea. (Unit: number of vehicle or facility).

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Number of ELVs (1000) (a)	611	679	653	813	762	735	711	737	735	761	821	890	862
Number of dismantling facilities (b)	417	435	458	485	509	515	522	510	516	520	535	543	556
Number of ELVs per dismantling facility (a/b)	1464	1561	1427	1677	1496	1427	1363	1445	1474	1464	1535	1640	1551

(Source: KECO, Internal Data, 2021) [48].

In Table 3, the recycling amounts and rates of ELVs between 2013 and 2020 in South Korea are presented. The recycling rates stayed relatively constant over the years and did not meet the national mandatory target rate of 95%. Many components of ELVs are recovered for re-use and recycling during the dismantling and shredding processes. The generation of ASR accounts for approximately 7.9% of the total ELVs in 2020. The recovered refrigerants during the dismantling processes slightly increased to 58 tons until 2019 but decreased in 2020. Many of the refrigerants from ELVs are emitted into the atmosphere partly due to the lack of strict enforcement by local authorities [49].

Table 3. Generation and recycling rates of ELVs in South Korea.

	2013	2014	2015	2016	2017	2018	2019	2020
Generation (1000 ton)	940.6	927.8	981.8	1019.0	1148.3	1162.8	1313.6	1250.2
Export (1000 ton)	120.0	110.0	138.5	125.2	141.2	116.1	301.4	258.8
Domestic treatment of ELVs (1000 ton)	820.5	809.8	843.3	893.8	1007.1	1046.7	1012.6	991.4
Recycling rate (%)	88.7	88.7	89.0	88.8	89.1	89.3	89.1	88.9
Total recycled and reused (=a+b+c+d) (1000 ton)	727.8	717.9	750.3	793.3	897.8	880.5	901.7	881.3
Recycled and reused by disassembly facilities(a) (1000 ton)	506.0	504.4	468.3	495.8	561.7	543.3	567.1	529.7
Recycled amount by shredding facilities(b) (1000 ton)	215.6	191.8	251.1	238.3	278.8	269.5	269.2	273.3
Recycled amount by ASR recycling facilities(c) (1000 ton)	4.2	21.7	30.9	59.1	58.0	63.6	65.5	78.3
Recovered refrigerants (d) (ton)	0	0.5	11	50	64	58	58	39

(Source: KECO, Internal Data, 2021) [48].

3.2. Analytical Results of PBDEs in ELVs

Table 4 presents the analytical results of PBDEs in various components of ELVs in this study. Out of a total of 36 samples from ELVs, only six samples were detected to have PBDEs above the detection limit of 1.0 mg/kg. Relatively high concentrations of PBDEs were found in seat fabrics, ranging from 2587 mg/kg to 37,498 mg/kg with an average of 14,752 mg/kg for the detected samples. Only two samples from automobile shredded residues contained a significant amount of PBDEs, at an average of 2919 mg/kg. In a previous study, the seat fabrics and ASR were also the main sources of PBDEs found in ELVs [42]. When compared with the previous study, the average concentration of ASR found in this study is 2.7 times higher (1076 mg/kg). On the other hand, the average concentration of PBDEs in seat fabrics in this study is much lower than that of the previous study (46,098 mg/kg). There can be variations of PBDEs in ASR and seat fabrics, depending on the ASR-treatment process as well as the model and type of ELV and the sampling practices. No PBDEs were detected in the other samples above the detection limit.

Table 4. Analytical results of PBDEs in components of ELVs. (Unit: mg/kg).

Components	Number of Samples Analyzed	Number of Samples Detected	Concentration Range	Average of Detected Samples
Seat fabrics (cover, foam)	10	4	2587~37,498	14,752
Dashboard, indoor lights, seatbelts	11	0	<1.0	<1.0
Ceilings and floor cover	9	0	<1.0	<1.0
Automobile shredded residues	6	2	312~5525	2919
Total	36	6	312~37,498	8836

Figure 2 shows the levels of PBDEs in ELVs that were detected by the XRF and GC/MS analyses of a variety of plastic components in this study as well as the previous study [42]. As shown in Figure 2, seat fabrics (e.g., seat cover and seat foam) and ASR contained relatively high levels of PBDEs in ELVs. The detection rates were 21.7% (10 out 46 samples) for seat fabrics, while the ASR samples with the high detection rate of 75% (12 our 16 samples) contained PBDEs at an average of 1247 mg/kg. Indoor-light-plastic-cover and floor-cover materials often showed significant levels of PBDEs, but lower detection rates (22.2% for indoor light covers and 23.8% for floor covers and roof materials) were found.

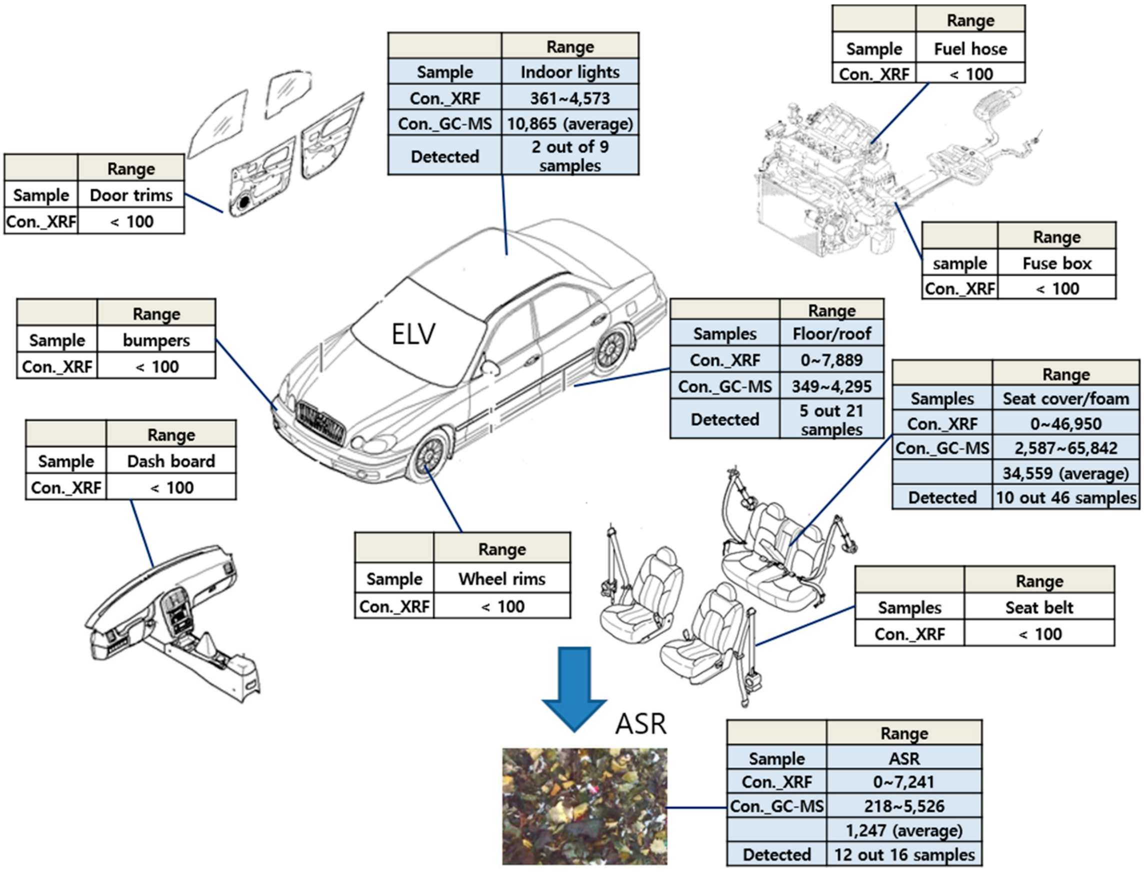

Figure 2. Occurrence and range of PBDEs in plastic-waste streams in ELVs (unit: mg/kg).

3.3. MFA Result of ELVs by Life Cycle

Figure 3 illustrates the material flow of ELVs in South Korea in 2020. As of 2020, approximately 4.49 million tons of new automobiles (or 3.51 million automobiles, assuming that one passenger vehicle is 1180 kg on average) were manufactured, 2.4 million tons (or 1.9 million automobiles) were exported and 0.37 million tons of cars were imported. The demand for the domestic automobile market was 2.4 million. Approximately 54.4% of the total production rate was consumed by the domestic market. The number of automobiles in use on the road was estimated to be 24.3 million (or 31.1 million ton) in the year. The total amount of the ELVs generated by deregistration was about 991,445 tons, which is equivalent to 775,000 vehicle units. Some of the ELVs were exported for international trade (258,000 tons). Approximately 81.0% of the ELVs were dismantled or disassembled into auto parts for re-use and material recycling (803,000 tons). During the dismantling processes, many recyclables and reusables (e.g., engines, transmissions, bumpers, radiators, oil tanks, lamps, air conditioners, batteries, tires, rims, power trains, doors, airbags, catalysts, and other reusable parts) are commonly recovered by the manual and mechanical disassembly processes. The depollution process is also commonly performed by removing engine/transmission/brake oils, fuels, and refrigerant gases. After dismantling, the remaining fraction of car hulks is sent to on-sites or off-site shredding facilities. The shredded materials are crushed and separated by mechanical processes including magnetic separators, eddy-current separators, electrostatic separators, density separators, trammel and vibrating screens, and air classifiers to recover ferrous and non-ferrous metals (67%). In 2020, approximately 273,000 tons of the metals were recovered for the steel-making industry and smelters. The remaining fraction (78,000 tons) of ASR was sent to the treatment facilities for either incineration with thermal recovery (47,000 tons) or without heat recovery (30,000 tons).

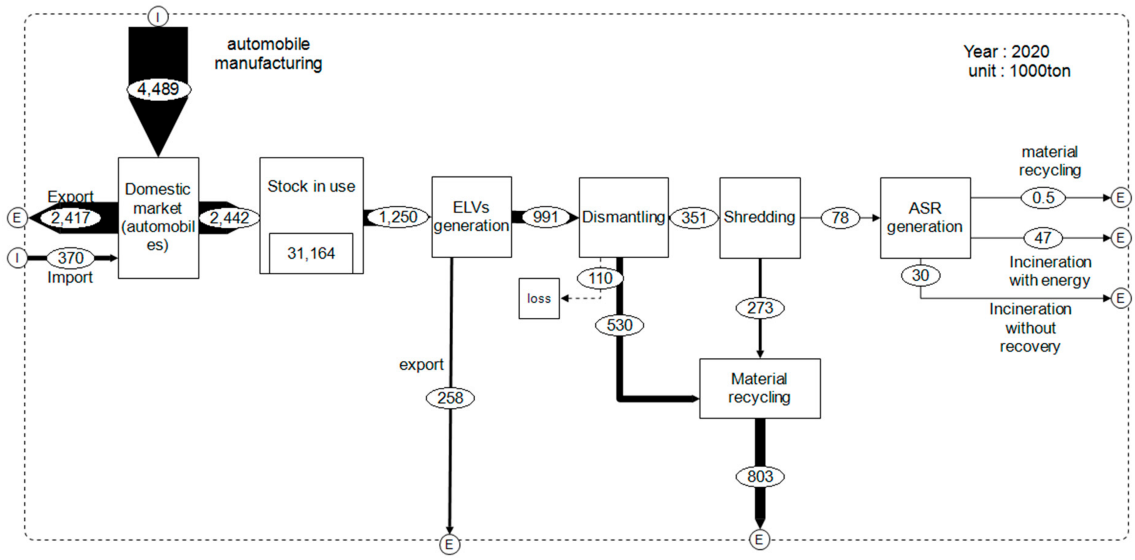

Figure 3. The result of MFA of ELVs by life cycle in South Korea (2020).

Figure 4 presents the substance flow of PBDEs in ASR from ELVs in South Korea. Most PBDEs present in ASR were processed for energy recovery (58 tons) or incineration (38 tons). It should be noted that there are no regulations on the monitoring of air emissions from brominated dioxins and furans upon incineration with or without energy recovery in South Korea, although brominated dioxins can occur during the incineration of BFR-containing plastics [17,42,50–52]. No data regarding the levels of brominated dioxins and furans from stack samples by emission monitoring of the facilities with ASR treatment have been reported so far.

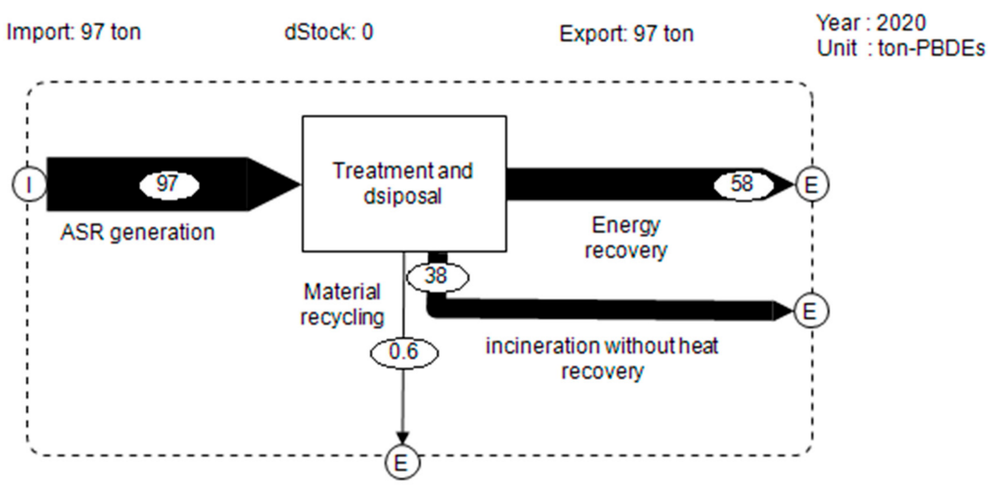

Figure 4. The result of SFA of PBDEs in ASR from in South Korea (2020).

4. Challenges and Suggestions

The current recycling rates (88.9% in 2020) of ELVs do not meet the national mandatory recycling target of 95%. There are still some fractions of ELV components that are treated at incinerators due to the lack of economically feasible recycling of ASR with potentially toxic elements. To divert such flow, more recycling and energy-recovery efforts for dismantled and shredded residues should be made in order to recover potential recyclables. However, since relatively high levels of PBDEs with an average of 1247 mg/kg may still be present in ASR, cautions should be taken when they are recycled or treated at incinerators. For example, PBDE-containing ASR materials may be limitedly recycled as secondary raw plastics with restricted uses or destroyed for the prevention of the dispersion of PBDEs in the environment. When ASR is incinerated, proper treatment and monitoring are required in order to control the brominated dioxins and furans that may form [51,52]. The levels and formations of brominated dioxins and furans during incineration and energy-recovery processes with ASR in South Korea are still unknown so far. A further study associated with the potential environmental impacts is warranted in the future. In Switzerland, due to the concern, the maximum percentage of ASR is limited up to 5% by mass when co-incinerated with other waste materials. Thus, the unintentional release of dioxins and furans upon improper incineration should be regularly monitored to control their dispersion in the environment [53–55]. Recently, the best available techniques and environmental practices for the recycling and disposal of wastes containing PBDEs have been proposed by the United Nations Environment Programme (UNEP) in order to provide guidance for the relevant waste-treatment and recycling industry [55]. More efforts toward the development of environmentally sound treatment technology of ASR along with mandatory target recycling rates have to be made in order to recover any valuable resources and remove toxic substances (e.g., PBDEs and heavy metals) during its treatment processes because the current recycling practices of ASR in South Korea involve rudimentary sorting and crushing processes without the application of aggressive recovery processes.

Currently, reporting systems on recycling amounts, manufacturing, import/export of vehicles, recovery and destruction of refrigerants, and treatment of ASR are available. However, there is a lack of financial incentives in the current management system. There has been a debate regarding the scope and roles of physical and financial responsibilities among the stakeholders (e.g., producers, recyclers, consumers, and government) in the current ELV-recycling system in South Korea. To improve the current recycling system, extended producer responsibility (EPR) should be adopted and implemented in ELV recycling with a clear responsibility for each stakeholder. Figure 5 presents a proposed EPR system for ELVs with financial, material and information flows among the stakeholders. Producers (i.e., manufacturers and importers) should take full responsibility for vehicles by life cycle from manufacturing to disposal, providing financial supports to treat refrigerants, ASR, and other non-recyclables. The revised mandatory target of 95% recycling can be achieved by the producers with such a support system for dismantling, shredding, and ASR-processing facilities.

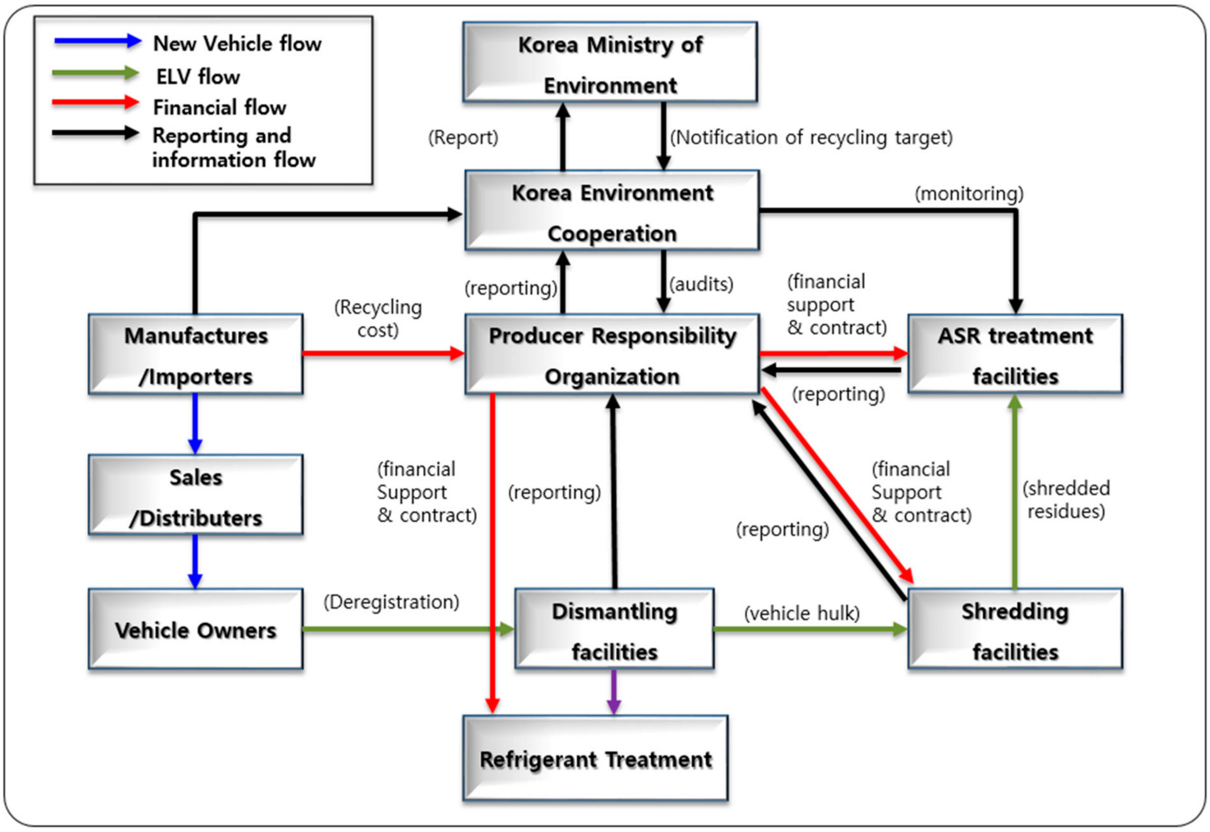

Figure 5. The proposed EPR system of ELVs management in South Korea.

5. Conclusions

The recycling of ELVs has been commonly practiced in many developed countries in order to recover reusable and recyclable components. It is important to properly treat any potentially toxic elements such as oils, fluids, refrigerants, anti-freeze, flame retardants, and heavy metals in ELVs from the perspective of pollution prevention that may result in serious human health problems and environmental impacts upon improper disposal. Thus, the environmentally sound management and resource recovery of ELVs towards a circular economy is an important issue of concern around the world. This study presents the current efforts toward the recycling and management of ELVs in South Korea. Based on the result of the MFA, approximately one million tons of ELVs were generated and processed by dismantling and shredding treatment and recovering reusable and recyclable parts (881,321 tons) in 2020. The current management system of ELVs achieved a total re-use and recycling rate of 88.9%, which is lower than the national target recycling rate of 95%. The remaining fractions of automobile shredded residues and seat-fabric foams were treated by energy recovery and incineration. Based on the analysis of PBDEs from 36 samples in ELVs, two main fractions (seat fabrics and ASR) contained significant levels of the chemicals during the recycling and disposal stages. Consequently, the proper management and monitoring of PBDEs in ELVs are needed in order to minimize their potential dispersion in the environment upon treatment and disposal. One of the major challenges of ELVs in the recycling industry in South Korea is the lack of economic incentives and support systems for economically low-value materials such as ASR, airbags, and seat foams, which are often treated or disposed of without resource recovery or proper treatment. This is one of the reasons for failing to meet the national recycling target rate of 95%. Producers (i.e., manufacturers and importers) need to play a significant role in the current ELV-recycling system by financially supporting the ELV-recycling-and-treatment industry to process such materials. More economically feasible and advanced recycling technologies are also needed in order to recover valuable metals and other resources, as well as to remove toxic chemicals (e.g., PBDEs, heavy metals) from ASR for toxic-free or clean recycling towards more sustainable resource management.

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