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Feasibility Study of Closed-Loop Recycling for Plastic Generated from Waste Electrical and Electronic Equipment (WEEE) in South Korea

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Abstract: Plastics follow a linear economic structure, leading to detrimental environmental effects, such as global warming and ecosystem destruction, through incineration and accumulation throughout their life cycle. This study examined the types, potential generation amounts, and properties of recycled plastics from waste electrical and electronic equipment (WEEE) to assess the feasibility of the closed-loop recycling of plastics from WEEE under South Korea's EPR system. Actual data from companies were used to determine the factors, such as the processing volume of WEEE. As of 2021, acrylonitrile-butadiene-styrene (53,363 tons), polypropylene (14,320 tons), and polystyrene (8199 tons) were the recycled plastics produced by both large and small WEEE. The properties of recycled plastics meet the specifications of new electrical and electronic products. In addition, an analysis using Life Cycle Assessment (LCA) methodology showed that the recycling effect (avoided emissions) reached 262,033 tons of CO_2 eq. per year. Therefore, closed-loop recycling is the most suitable and effective method for reducing greenhouse gases. This paper presents the potential amount of recycled plastics generated from WEEE within South Korea's regulatory framework, providing valuable foundational data for policy development for promoting the use of recycled plastics.

Keywords: closed-loop recycling; waste electrical and electronic equipment; circular economy; recycled plastic; greenhouse gases; Extended Producer Responsibility

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1. Introduction

The invention of plastic has had a significant impact on human life. Plastic use is ubiquitous in many areas, such as healthcare, food, and industry. On the other hand, the use of plastic has led to an increase in plastic waste, which has become a significant environmental issue.

Global plastic production has increased from approximately 2 million tons in 1950 to around 460 million tons in 2019, based on the data from Our World in Data [1]. Accordingly, plastic waste has been measured to be 353 million tons. In 2020, the COVID-19 pandemic led to decreased production from the automobile and trade industries, resulting in a partial decrease in plastic production. Nevertheless, the production and disposal of plastic have increased because of the use of medical masks and packaging waste.

The issue of plastic waste has focused on packaging materials. According to Statista, packaging plastics account for 39.1% of the total plastic demand. Hence, the EU has been implementing policies, such as the "Single-Use Plastics Directive" and "Plastic Bags Directive" [2,3]. Furthermore, e-waste is another significant issue that has gained recent attention.

E-waste is electronic waste commonly generated from televisions, refrigerators, and computers. The electronics industry has a significant plastic content, but the generation of e-waste continues to increase because of the advances in the IT industry and shorter product lifecycles. Unfortunately, the rate of e-waste recycling remains alarmingly low, with an estimated loss of approximately 80% [4]. Plastics from discarded e-waste are typically incinerated or sent to landfill, contributing to substantial greenhouse gas emissions.

The disposal of e-waste has become a global problem, particularly because of its significant impact on climate change and resource depletion. In response, countries worldwide have been focusing on a circular economy and resource circulation [5–8]. In the economic system, a circular economy is considered a key solution to reducing environmental impacts. The key economic strategies include material design, material reduction, reuse, recycling, and renewable energy [9,10]. Table 1 lists the policies of key countries regarding resource circulation and the circular economy for E-waste [11–13].

Table 1. Policy on resource circulation of waste electrical and electronic products in major countries.

Classification		Contents
EU	WEEE Directive	For electronic products with a rated voltage of up to 1000 V AC and 1500 V DC, when they reach the end of their lifespan, their collection, treatment, and recycling contribute to sustainable production and consumption improvements, increased resource efficiency, and the promotion of a circular economy.
	New circular economy action plan	The design implementation follows eco-design regulations, prioritizing factors such as device efficiency, durability, repairability, and upgradeability and considerations for maintenance, reuse, and recycling.
USA	New York State	Manufacturers must establish systems for collecting, managing, recycling, or reusing waste products for small electronic products, such as computers, televisions, and computer peripherals. They are also required to operate and maintain electronic waste disposal programs.
	Texas State	An individual producer responsibility system is applied, requiring manufacturers to collect and recycle their products. They must prepare and submit an annual report specifying the weights associated with the collection and recycling processes.
Japan	The Small Electronic Waste Recycling Promotion Law	Under an individual producer responsibility system, manufacturers must collect and recycle their products. They must also prepare and submit annual reports that include the weight of products collected and recycled during the designated process.
China	Regulation on the Collection and Disposal Management of Waste Electrical and Electronic Products	Design techniques are applied to support resource conservation and adopt environmentally sound waste-disposal methods. Product recycling information and information on toxicity and hazardous substances are provided to aid this effort.

The EU announced the Ecodesign for Sustainable Products Regulation (ESPR) in March 2022. This regulation expands the scope of ecodesign requirements from Energy-using Products [14] (EuP) and Energy-related Products [15] (ErP) to all physical products. Information regarding the recycling content, recyclability, and environmental footprint related to the functional requirements of the products must be provided [16].

In South Korea, the Environmental Guarantee System was implemented on 1 January 2008, following the enactment of the “Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles” in 2007. This system restricts the use of hazardous substances and promotes the recycling of electrical and electronic products and vehicles. The system consists of pre-emptive and post-management regulations. For electronics, it includes the management of hazardous substance content standards and compliance with material and structural improvement guidelines. The latter part distinguishes the responsibility of the producers and sellers for collecting and transferring electrical and electronic products. Currently, for packaging materials, the Extended Producer Responsibility (EPR) system is implemented under Article 16 of the "Act on Resource Conservation and Promotion of Recycling". For electrical and electronic products, it is implemented under Article 5 of the "Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles". The EPR system ensures that producers take a central role in the entire process, from the production to recycling of their products. Since 2021, 49 designated products from five waste electrical and electronic equipment categories have been managed under this system.

In addition, four policy attempts have been made to increase the recycling rates and reduce the waste related to plastics in South Korea [17–20]. In the "K-Circular Economy Implementation Plan", provisions were made to allow the labeling of recycled content usage in products or containers and promote the establishment of a recycled content certification system linked with the Good Recycled (GR) product certification. Subsequently, a memorandum of understanding was signed on 28 December 2022 to establish a high-quality recycling system linked with GR certification. Discussions were held on the testing, analysis, evaluation, and certification of recycled materials and products.

Efforts in resource circulation are needed because electrical and electronic products contain a significant amount of plastic. The most effective way to improve the resource productivity of plastics is through closed-loop recycling, where post-consumer plastic waste returns to the production process as raw materials [21–23]. Closed-loop recycling is the ideal method for resource circulation and a circular economy because it involves materials or energy circulating within similar product systems. Therefore, research on the supply of recycled materials, the properties of recycled materials, and the possibility of replacing virgin materials with recycled materials is essential for establishing the current and circular economy-oriented recycling systems. One of the academic techniques is the Life Cycle Assessment (LCA). The LCA methodology is used globally to assess closed-loop recycling. This methodology, which is internationally recognized and provides quantitative evaluations of environmental impacts throughout the entire life cycle, from raw-material acquisition to disposal, enables quantification of the environmental impacts of recycling systems based on scientific evidence [24].

Figure 1 presents the recycling types of recycled materials from a closed-loop perspective. The recycling types are categorized as (A), (B), or (C) depending on which stage of the product life cycle the recycled material is reintegrated into. In the case of (A), the recycled material is reproduced immediately into a final product through recycling processes. This results in significant environmental impact reduction by saving raw materials and energy required in the production stage. In contrast, (C) involves reducing energy and material use during raw-material sourcing. One prominent example is chemical recycling through the production of recycled plastics. Although the greenhouse gas reduction effect may appear slightly lower than that for the other recycling methods, (C) holds great significance because of its high utilization in the production stage as a transition to raw materials.

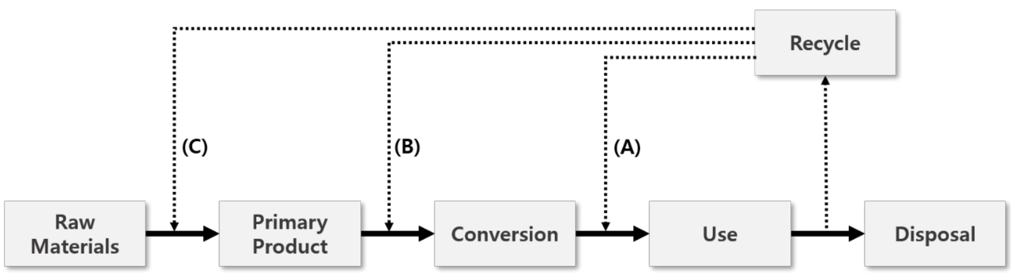

Figure 1. Types of closed-loop recycling models.

Thus, this study examined the potential for closed-loop plastic recycling within the electrical and electronic products industry to foster resource circulation and a circular economy. Figure 2 outlines the specific objectives for this purpose.

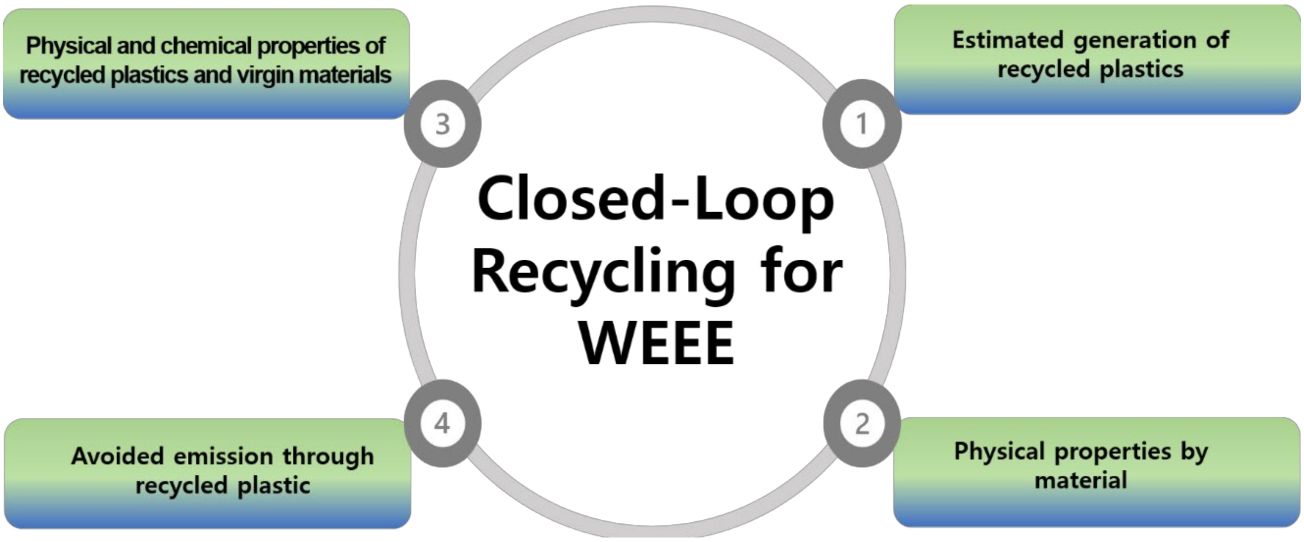

Figure 2. Specific objectives for assessing the closed-loop recycling potential of plastics within the electrical and electronic products Industry.

2. Materials and Methods

2.1. Estimation of the Generation of Recycled Plastics

Table 2 lists the amount of recycling of 49 items managed according to the WEEE Producer Responsibility System as of 2021. The total recycled amount of all treated items in 2021 was 427,238 tons. Among them, the throughput of five large appliances (including refrigerators, washing machines, air conditioners, televisions, vending machines, and heat exchangers) was 300,639 tons, and the throughput of 44 small- and medium-sized appliances was 126,599 tons.

Table 2. Recycling quantities by product category under the EPR Recycling System in 2021.

Category	Product	Recycling Amount (ton)
Temperature Exchanger	Refrigerator	191,349
	Electric water purifier	17,786
	Vending machine (including temperature exchange function)	1032
	Air conditioner	8654
	Dehumidifier	263
Display Device	Television	29,178
	Computer (e.g., monitors and laptops)	2100
	Navigation system	10
Telecommunication equipment	Computer (main unit, components, and peripherals)	12,290
	Copiers	4238
	Printers	5280
	Fax machines	146
	Scanners	38
	Beam Projectors	37
	Wireless routers	107
	Mobile phone handsets	84

Table 2. *Cont.*

Category	Product	Recycling Amount (ton)
General electric/electronic products	Washing machines	70,426
	Electric ovens	382
	Microwaves	1302
	Food waste disposers	72
	Dish dryers& Dishwashers	1151
	Electric bidets	1755
	Air purifiers	3521
	Electric heaters	33
	Audio systems	324
	Electric rice cookers	1175
	Water softeners	289
	Humidifiers	32
	Electric irons	82
	Fans	161
	Blenders	73
	Vacuum cleaners	423
	Video players	21
	Toasters	20
	Electric kettles	30
	Electric water heaters	36
	Electric frying pans	56
	Hair dryers	16
	Treadmills	504
	Surveillance cameras	4
	Food dehydrators	10
	Electric massagers	3277
	Foot baths	18
	Sewing machines	12
	Video game consoles	10
	Bread makers	26
	Deep fryers	47
	Coffee makers	124
	Herbal medicine baths	38
	Spin dryers	12
	Vending machines (excluding temperature exchange functions)	33
	General electric/electronic products mixture	69,151
	Total	427,238

The EPR includes two categories of products (large-scale and medium-small-scale) based on the size of the target products (currently classified and managed into five product groups, including thermal exchangers). Recycling facilities handling these products vary between companies. S Company helps process large waste electrical and electronic products, while M Company is a prominent company handling medium-small-scale waste electrical and electronic products. Therefore, a sample survey was conducted on these two companies to estimate the potential generation of recycled plastics. In addition, cooperation was sought from a recycled-raw-material producer, C Company, to assess the feasibility of recycling plastics.

Figure 3 presents the flow of collection and recycling of domestic electrical and electronic products. Discarded consumer electrical and electronic products are collected through the legal system and transported to different recycling facilities based on size. Each recycling facility recycles electrical and electronic product waste. The resulting plastics are transported to a recycled plastics production company to be supplied as recycled plastics for manufacturing. Nevertheless, not all plastics are being transported to recycled plastic production companies. Currently, only a fraction of plastics are being transported and processed by recycled plastic companies for supply to manufacturers. Therefore, this study assumed that all plastics generated within the legal framework are being transported and processed by recycled plastic production companies and estimated the potential generation of recyclable plastics available within the legal framework as of 2021.

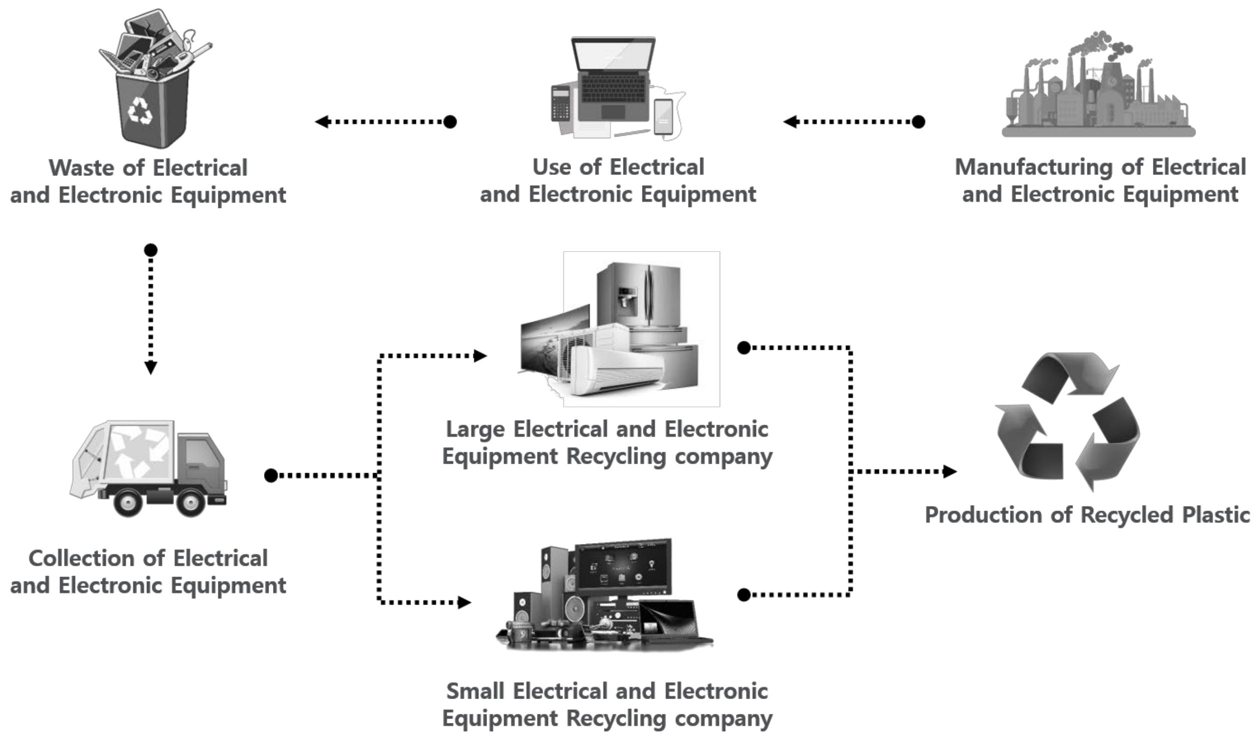

Figure 3. Flowchart of domestic resource circulation of recycled plastics from WEEE.

2.2. Physical Properties by Material

A specific gravity balance (ALFA MIRRAGE EW-300SG) (version MDS-300), a universal material testing machine (Qmesys QM100T-2T), and an Izod impact testing machine (Qmesys QM700A) were used to determine the basic properties of plastics. The results of dismantling and disassembling the WEEE indicate that ABS (acrylonitrile butadiene styrene), PP (polypropylene), and PS (polystyrene) constitute the majority of the plastic waste by weight. At the same time, the remaining portion is classified as other plastics. ABS, PP, and PS can be recycled for secondary use. On the other hand, other plastics are either distributed as mixed plastics or disposed of as waste because of their limited quantity, regulations on hazardous substances, economic feasibility, and unsuitability for recycling purposes. Therefore, the potential generation and properties of recyclable ABS, PP, and PS were examined to assess the feasibility of closed-loop recycling.

2.3. Physical and Chemical Properties of Recycled Plastics and Virgin Plastics

The physical and chemical properties of the recycled plastics were measured, including tensile strength, elongation at break, impact strength, specific gravity, melt flow index, flexural strength, flexural modulus, and hazardous substances. Among these properties, the specific gravity, impact strength, flexural modulus, and tensile strength were selected as critical points for comparing recycled resin with virgin resin. This selection was based on these four properties being fundamental indicators of the resin performance. The melt flow index can vary according to the manufacturer's request or specific purposes. Hence, it was used as a reference property in this study.

2.4. Greenhouse Gas (GHG) Emission Avoidance through Recycled Plastics

The plastic materials received from each recycling center undergo separation, loading, and various processes depending on their form and type, as shown in Figure 4. These processes include density separation, material sorting, and washing to remove contaminants and flame retardants. In addition, a wet sorting process is conducted to enhance the purity, which results in the mixing of plastics with similar densities. Additional sorting processes, such as optical and electrostatic sorting, are implemented in such cases [25].

Non-shredded plastics are introduced into a dry sorting process where workers remove impurities and sort materials manually, eliminating various foreign substances and flame retardants. Therefore, recycled plastics are produced through a combination of wet sorting, dry sorting, optical sorting, and electrostatic sorting, where the primary purpose is to blend and produce the desired mixture of plastics for specific applications.

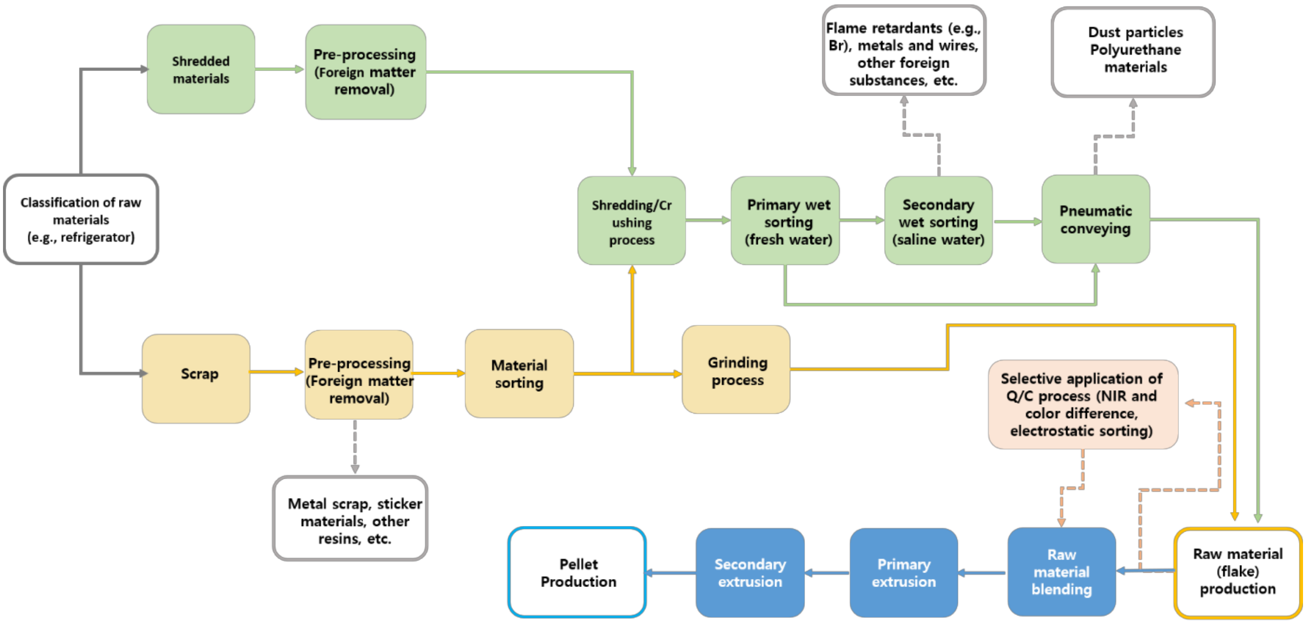

Figure 4. Production process of recycled plastics designed by C Company.

The use of recycled plastics promotes resource circularity and can further reduce GHG emissions. This study adopted LCA methodology, which is used widely in various industries and sectors because it is an appropriate approach to assess the GHG avoidance effect resulting from raw-material substitution.

3. Results and Discussion

3.1. Generation of WEEE and Plastic Waste as the Subject of Investigation

3.1.1. Generation of Recycled Plastics from Large-Scale WEEE

Table 3 lists the production of recycled plastics at various stages from the 5868 tons of plastic transferred from the sample Company S, which represents the processing of large household appliances (refrigerators, washing machines, air conditioners, TVs, and vending machines) to a recycled plastic production facility. The table lists the production volume of recycled plastics according to the type and the number of recycled plastics available to manufacturers. The physical properties of recycled plastics, known as PCR (Post-Consumer Recycled) materials, deteriorate during their usage, and the quality degrades during the manufacturing stage because of factors such as urethane, plating, and flame retardants. Of the total plastics generated from the incoming post-consumer electronic waste, only 3421 tons, which accounts for 58% of the plastic quantity, are available as reusable PCR materials from a closed-loop recycling perspective (Figure 5). This excludes the materials categorized as "Others", such as GFPP, composite PP, ABS-GF, and flame retardants, which manufacturers do not handle. Moreover, only materials that meet the requirements for physical properties, color, and hazardous substance regulations can be reused, even for ABS, PP, HIPS, and GPPS.

Table 3. Generation of plastic produced by S Company and available plastic supply from manufacturers in 2021.

	ABS	PP	PS	Others	Total
Weight (ton) *	2464	997	880	1526	5868
Weight (ton) **	2406	645	370	-	3421
Proportion (%) ***	97.7	64.7	42	-	58.3

* Generation of plastic by material type produced by S Company; ** generation of recycled plastics by type available from manufacturers; *** Proportion (%) = quantity of recycled plastics available from manufacturers/generation of plastic produced by type.

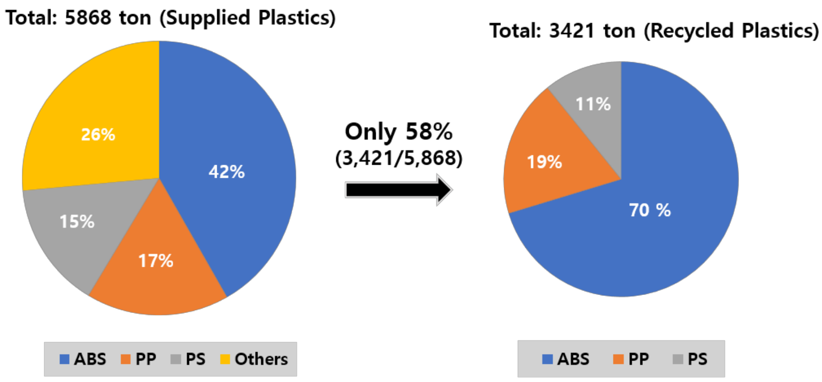

Figure 5. Types and quantities of plastics derived from large-scale WEEE and amount of material available to be reused.

The total amount of recycled plastic generated from large-scale WEEE can be estimated within the regulatory jurisdiction in 2021 based on the plastic generation ratios according to the type and amount of plastic available for supply to manufacturers from S Company, a representative recycling facility for large-scale WEEE samples, as expressed in Equation (1).

$$PE_{large\ WEEE} = TV_{large\ WEEE,2021} \times \frac{SV_{supply}}{SV_{large\ WEEE,2021}} \quad (1)$$

where $PE_{large\ WEEE}$ is the potential generation amount of recycled plastics within the total large-scale WEEE; $TV_{large\ WEEE,2021}$ is the total processing volume of large waste electrical and electronic equipment (2021); SV_{supply} is the volume of (recycled) plastics available for supply to S Company's manufacturers (Yongin, Republic of Korea); and $SV_{large\ WEEE,2021}$ is the processing volume of large-scale WEEE by S Company (2021).

In 2021, 300,639 tons of large WEEE were collected and recycled within the regulatory jurisdiction. Among these, plastic generation amounted to 71,408 tons. Hence, the estimated amount of recycled plastic and resin for that year can be determined, as shown in Table 4. The distribution of plastic types follows the same ratios as the plastic generation rates from S Company in Table 3.

Table 4. Generation of plastic within the entire Large-scale WEEE and quantity of recycled plastics available for supply to manufacturers.

	ABS	PP	PS (HIPS + GPPS)	Others	Total
Weight (ton) *	32,801	13,277	11,715	20,306	78,099
Weight (ton) **	32,020	8591	4920	-	45,531

* Generation of plastic by material type within the entire large-scale WEEE in 2021; ** quantity of recycled plastics available by material type for supply to manufacturers from large-scale WEEE.

This study estimated the generation of available plastics according to the type within the regulatory jurisdiction based on the actual case of S Company. Although there may be variations in the generation rates at different recycling centers because of the production yield, the reliability of the data is considered high because of the overall standardization of processing facilities at recycling centers nationwide and the application of common legal recycling rates for target products. Therefore, the data are significant because they estimated the generation of available PCR materials for new electrical and electronic product production within the closed-loop recycling framework in South Korea in 2021.

3.1.2. Generation of Recycled Plastics from Small- and Medium-Scale WEEE

The data from M Company, a recycling company specializing in the recycling of medium and small electrical and electronic products, were used to estimate the generation of recycled plastics from 44 obligated products, excluding the five large electrical and electronic products. This company handles most of the obligated products, excluding the large electrical and electronic products, as shown in Supplementary Table S1. Therefore, it was considered a suitable sample for the survey.

In 2021, M Company processed 7800 tons of medium and small electrical and electronic products, resulting in the generation of plastic by type, as shown in Table 5. ABS, PP, and PS were the most significant contributors. The total amount of these major plastics generated was 3205 tons, with ABS, PP, and PS accounting for 1346 tons, 545 tons, and 481 tons, respectively. Other plastics, such as ABS flame retardant, PA, PE, PC, PET, ABSFR, AS, and PCABS, were also generated, albeit in small quantities, so they were excluded. The generated ABS, PP, and PS (3205 tons) were delivered to a recycled plastic company. They underwent a recycling/sorting process, generating the same proportion (26%) of miscellaneous plastics (including waste plastics). The generation of recycled plastics was estimated based on this assumption.

Table 5. Generation of plastic produced by M Company and available plastic supply from manufacturers in 2021.

	ABS	PP	PS	Others	Total
Weight (ton) *	1346	545	481	833	3205
Weight (ton) **	1315	353	202	-	1870
Proportion (%) ***	98	65	42	-	58.3

* Generation of plastic by material type produced by Company M; ** generation of recycled plastics by type available from manufacturers; *** Proportion (%) = quantity of recycled plastics available from manufacturers/generation of plastic produced by type.

Furthermore, four samples were surveyed per manufacturer to identify the forms of plastic generated by each type of medium and small electrical and electronic products; Table 6 lists the results. The investigation of plastic generation by each type showed that in medium and small electrical and electronic products, ABS was generated predominantly by dehumidifiers (27%), air purifiers (70%), water purifiers (16%), and blenders (16%). PP was present in rice cookers (26%), vacuum cleaners (34%), bidets (35%), and similar products. PS was prevalent in audio equipment (43%), printers (43%), computer vending machines (69%), and similar devices. These findings suggest that in the future, sorting methods can be used to obtain plastics with higher value characteristics when designing processes in specialized recycling companies for medium and small products.

Table 7 lists the amount of recycled plastic generated from all medium and small electrical and electronic products in 2021, using the same method to estimate the recycled plastic generation from the total large electrical and electronic products. The total processing quantity of medium and small products in 2021 was 126,599 tons; the estimated plastic generation was 52,019 tons. The recycled plastic generation ratios from S Company were applied. The potential amount of recycled ABS, PP, and PS plastic generated in 2021 was estimated to be 21,343, 5729, and 3279 tons, respectively. On the other hand, obtaining precise data on the actual amount of recycled plastic that can be supplied to manufacturers was challenging because it is considered a company trade secret. Therefore, the same ratios for the supply of recycled plastic to manufacturers as mentioned earlier for large electrical and electronic products were applied for estimation purposes.

Table 6. Generation forms of plastic from small- and medium-scale WEEE according to the waste categories.

Ratio (%)	**Dehumidifier (27)**	**Air Purifier (70)**	**Water Purifier (16)**
ABS			
Ratio (%)	Electric rice cooker (26)	Vacuum cleaner (34)	Electric bidet (35)
PP			
Ratio (%)	Audio system (43)	Printer (43)	Keyboard (69)
PS			

Table 7. Generation of plastic within the entire small- and medium-scale WEEE and quantity of recycled plastics available for supply to manufacturers.

	ABS	**PP**	**PS (HIPS + GPPS)**	**Others**	**Total**
Weight (ton) *	21,846	8846	7807	13,520	52,019
Weight (ton) **	21,343	5729	3279	-	30,351

* Generation of plastic by material type within the entire small- and medium-scale WEEE in 2021; ** quantity of recycled plastics available by material type for supply to manufacturers from small- and medium-scale WEEE.

The same as in Equation (1), the total amount of recycled plastic generated from small- and medium-scale WEEE was estimated using Equation (2).

$$PE_{s-m\ WEEE} = TV_{s-m\ WEEE,2021} \times \frac{SV_{supply}}{SV_{s-m\ WEEE,2021}} \quad (2)$$

where $PE_{s\text{-}m\ WEEE}$ is the potential generation volume of recycled plastics within the total small- and medium-scale WEEE; $TV_{s\text{-}m\ WEEE,2021}$ is the total processing volume of small- and medium-sized waste electrical and electronic equipment (2021); SV_{supply} is the volume of (recycled) plastics available for supply to S Company's manufacturers; and $SV_{s\text{-}m\ WEEE,2021}$ is the processing volume of small- and medium-sized waste electrical and electronic equipment by S Company (2021).

Table 8 lists the plastic generation according to the material and the amount of recycled plastic available to manufacturers from the total large electrical and electronic products and the medium and small electrical and electronic products in 2021. The total amount of recycled plastic was 130,118 tons, of which 75,882 tons were estimated to be available to manufacturers as raw materials for homogeneous products.

Table 8. Estimation results of plastic generation within the entire waste electrical and electronic equipment (WEEE) and quantity of recycled plastics available for supply to manufacturers.

	ABS	PP	PS (HIPS + GPPS)	Others	Total
Weight (ton) *	54,647	22,123	19,522	33,826	130,118
Weight (ton) **	53,363	14,320	8199	-	75,882

* Generation of plastic by material type within the entire WEEE in 2021; ** quantity of recycled plastics available by material type for supply to manufacturers from WEEE.

3.2. Physical and Chemical Properties of Recycled Plastics and Virgin Plastics

Figure 6 presents the properties of ABS, PP, and PS, including density, impact strength, flexural modulus, and tensile strength, derived from the recycling of large electrical and electronic products. These four properties were selected because they are fundamental indicators of resin performance. The five primary indicators of resin performance are impact strength, flexural modulus, density, tensile strength, and melt flow index. The melt flow index was excluded from the measurements and presentation because it is a measured data value provided upon request or for specific purposes by the manufacturers.

Table 9 compares the properties of ABS, PP, and PS derived from large and small electrical and electronic products. As listed in Table 9, the basic properties of recycled plastics, including the density, impact strength, flexural modulus, and tensile strength, were measured.

Small electrical appliance ABS may show variations in specific properties because of the production date and lot, but a uniform property profile can be observed overall. The difference in properties between small and large appliance ABS is minimal, suggesting that small appliance ABS could be applied partially to the non-visible parts of household appliances if the variations are assumed to be consistent.

The properties of small electrical appliance PS can vary according to the production date and lot. The properties of small appliance PS are similar to those of large appliance PS, except for the impact strength. Based solely on the properties, small appliance PS could be applied partially to non-visible parts of household appliances. On the other hand, the Br (bromine) content, a hazardous substance, is approximately 500 mg/kg (ppm), which exceeds the acceptable limits for household appliances (RoHS limit of 1000 ppm or lower, producer management standard of 500 ppm or lower) [26]. Therefore, careful consideration is needed to ensure that hazardous substances are not generated during the sorting process.

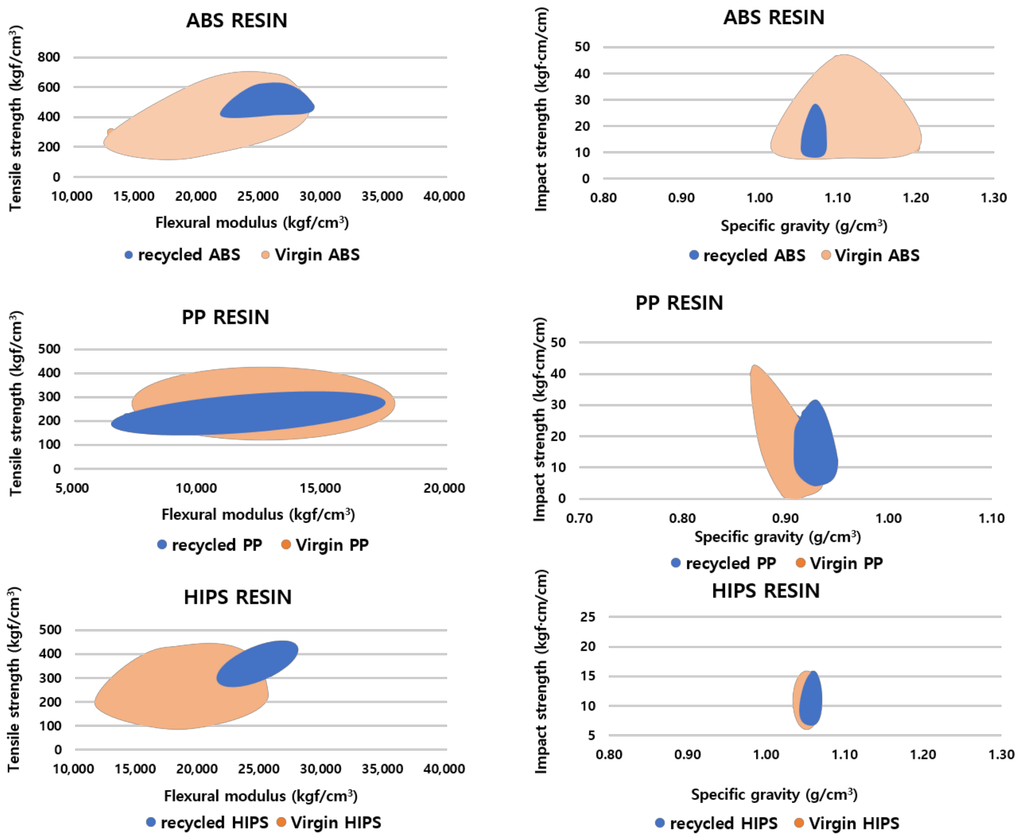

Figure 6. Comparison of the properties between recycled materials and virgin materials.

Table 9. Comparison of PCR materials within WEEE.

Test Type	Tensile Strength	Elongation	Impact Strength	Specific Gravity	Melt Flow Index	Flexural Strength	Flexural Modulus	Hazardous Substances
	50 mm/min Properties	3.2 mm	1/8 Notched, 3.2 mm	-	220 °C/10 kg	10 min/min, 3.2 mm		Br
Method	ASTM D638		ASTM D256	ASTM D792	ASTM D1238	ASTM D790		X-ray
Unit	Kgf/cm^2	%	kgf·cm/cm	g/cm^3	g/10 min	kgf/cm^2		mg/kg
LC ABS #1	498.33	15.24	12.65	1.07	17.20	825.88	26,993.93	169.0
LC ABS #2	501.08	15.94	12.89	1.07	20.10	822.41	25,768.24	157.6
LC ABS #3	504.65	14.76	12.01	1.07	18.80	837.93	26,696.83	176.1
SC ABS #1	493.90	16.38	11.69	1.06	19.40	807.95	26,151.13	153.6
SC ABS #2	495.77	14.95	11.95	1.06	22.52	805.14	25,862.27	141.8
SC ABS #3	496.66	21.82	11.66	1.06	21.38	788.06	25,165.980	145.6
LC PS #1	375.97	38.40	10.48	1.06	14.26	585.79	25,839.26	11.9
LC PS #2	385.53	36.45	10.44	1.06	14.88	599.01	24,447.04	5.1
LC PS #3	377.17	34.81	10.29	1.06	14.84	619.89	26,136.95	3.4
SC PS #1	333.00	27.71	8.04	1.05	16.38	548.61	23,580.14	581.6
SC PS #2	334.41	25.04	8.34	1.05	16.90	542.24	23,826.92	534.1
SC PS #3	338.98	30.99	8.73	1.05	15.92	547.31	24,233.79	576.2
LC PP #1	256.62	38.15	8.05	0.92	17.58	383.53	13,354.34	54.0
LC PP #2	253.02	47.19	8.95	0.92	17.00	339.62	11,559.86	66.4
LC PP #3	253.65	31.76	8.08	0.92	18.84	373.25	12,810.61	76.3
SC PP #1	287.89	122.54	5.18	0.95	7.20	340.23	11,870.05	115.5
SC PP #2	245.53	8.52	4.62	0.95	11.60	345.78	12,877.97	151.4
SC PP #3	252.01	34.72	7.04	0.94	8.08	332.11	11,842.88	99.1

LC: Large-scale WEEE, SC: small-scale WEEE.

Small electrical appliance PP exhibits significant property variations, such as elongation at break, impact strength, and melt flow index based on the production date and lot.

This variation is likely due to the inclusion of various additives [27], and it is speculated that the presence of high-density additives and the incorporation of compounds, such as talc, $CaCO_3$, or GF (glass fibers), are the main factors contributing to these variations. The high density, variation in elongation at break, and variation in melt flow index make applying small appliance PP to household appliances challenging. Therefore, using small appliance PP in household appliances may be difficult because of the significant property deviations.

A comparison of the properties of recycled plastics from large and small household electronic waste shows that small household ABS and PS exhibit some property variations. Small household PS has high levels of harmful bromine (Br), making it challenging to apply in electronic appliances. In addition, small household PP shows a high density and the potential inclusion of compounds or glass fibers (GF), making it less suitable for applications in electronic appliances. Therefore, only ABS is suitable for application in electronic appliances based on the tested samples. These results are based on a simple comparison of the properties, and additional evaluations, such as sensory assessments, surface characteristics, UL certification, and evaluations conducted by electronic manufacturers, are necessary for application in electronic appliances. Moreover, additional procedures, such as production facility evaluations, quality management, and stability verification, are also required. Further research will be needed on the following aspects in addition to the results obtained from the sample tests:

First, closed-loop recycling for small household ABS: Applying closed-loop recycling to ABS is feasible based on the current sample test results. On the other hand, the management of hazardous substances and standardization of the resin properties are required to expand the application of recycled plastics from small household electronic waste. Furthermore, the production of recycled resins should be differentiated between compounds, such as those causing high density, and glass fibers (GF). Furthermore, addressing these property variations will require lot-based production management (e.g., increasing the lot size from 1 to 10 tons) to ensure consistent quality.

Second, increased application of recycled plastics in new electronic products: Additional considerations are required to incorporate more recycled plastics into new electronic products. Currently, recycled plastics have been applied to non-visible parts of appliances. Application to external components poses challenges because of the constraints related to color and surface characteristics. Therefore, alternative approaches must be evaluated, such as lowering the material management standards for parts that allow the use of non-applicable recycled resins (e.g., compounds and GF).

Third, increasing the volume of recycled plastics: Increasing the generation of recycled plastics will require recycling companies to invest in facility upgrades to enhance sorting technologies, ensuring the production of usable recycled plastics without contamination. Moreover, the production of high-quality recycled plastics through multiple sorting processes, rather than simple treatments that result in low-grade recycled plastics, will help expand the production of high-quality recycled plastics. Support regarding regulations and facility investments is necessary for plastic recycling companies. Ensuring a stable supply of raw materials (plastic waste) is crucial. The production of usable recycled plastics can be enhanced if plastic recycling processes can differentiate between plastic and non-plastic materials at the pre-processing stage.

Finally, considerations for recycled plastic companies and manufacturers: Recycled plastic companies should consider the recycling efficiency, recycling technologies, and improved quality of recycled plastics. Manufacturers, however, should also consider eco-design strategies during the production stages of electronic products to increase the generation of recycled plastics.

Therefore, there is an urgent need for a plastic waste management strategy in Korea through a review of the regulations and policies of high-income countries, such as the United States, Japan, the EU, and the United Kingdom [28]. In addition, despite the many benefits of plastics, as plastics are recognized as a cause of serious environmental problems worldwide, it is essential to prepare environmental, political, and economic measures to maintain the role of plastics [29].

3.3. GHG Emission Avoidance through Recycled Plastics

Figure 7 shows the flow of PCR materials in electrical and electronic products. The required amount of PCR materials for producing virgin resins was estimated by retroactively summing-up the quantities of ABS, PP, and PS materials generated from electronic waste. Approximately 53,363, 14,320, and 8199 tons of ABS, PP, and PS, respectively, could be recycled from electronic waste in 2021. From a closed-loop recycling perspective, these recycled materials can help avoid the production of virgin ABS, PP, and PS materials by 98%, 65%, and 42%, respectively.

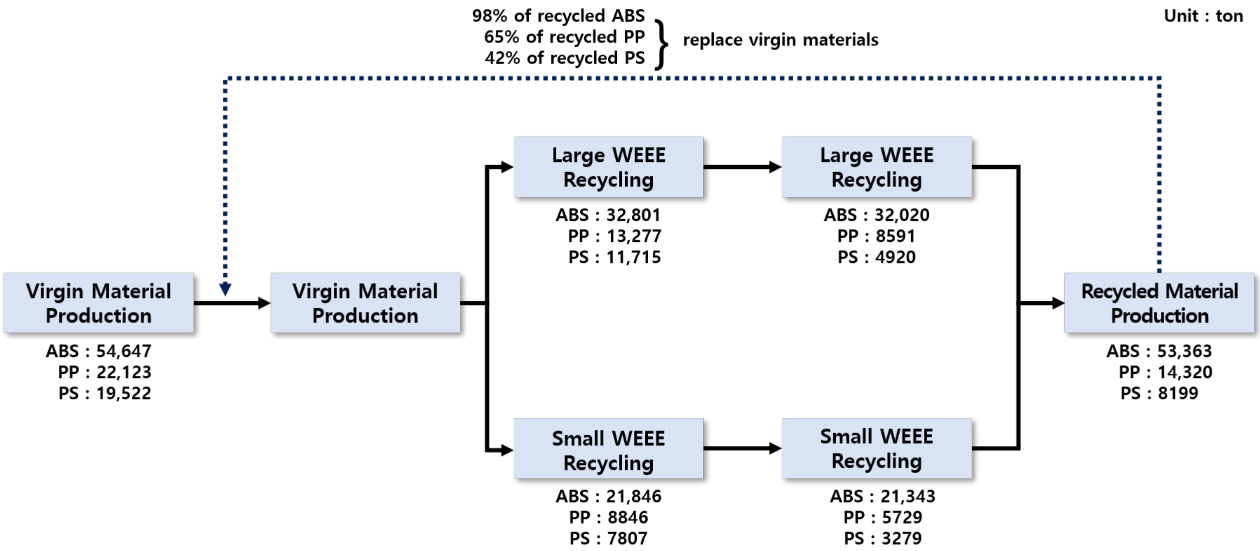

Figure 7. Flow of PCR within WEEE in the regulatory region as of 2021.

The LCA methodology based on ISO 14040 and ISO 14044 was used to calculate the GHG reduction [30,31]. This methodology explicitly states that one can avoid environmental impacts when end-of-life materials are replaced with virgin material in a loop format during the end-of-life stage. Several studies have analyzed the avoided effect of environmental impacts through material replacement [32–36]. On the other hand, this study differs in assessing the avoidance effect of plastics within electrical and electronic products, which have their specific properties.

Furthermore, an analysis of GHG reduction through closed-loop systems was also conducted because of the global emphasis on the common goal of GHG. LCA studies of e-waste have been carried out in various countries abroad, confirming a decrease in environmental impacts when using recycled materials compared with virgin materials [37–41]. On the other hand, the analysis of closed-loop recycling for WEEE in the Korean case is currently lacking.

In the context of LCA, substituting recycled materials for conventional materials can be quantified regarding GHG emission reduction. Ideally, the measurement data for each recycling process from specific recycling companies should be used as a priority for data. In this study, however, the next priority option, which uses established Life Cycle Inventory (LCI) databases, was employed. The calculation method for GHG emissions using LCI databases is expressed as Equation (3). This study used the internationally recognized Ecoinvent and Ecosystem databases, and the IPCC Fifth Assessment Report (2013) Global Warming Potential (GWP) 100-year values were applied for GHG emissions. The LCI database for the production of PCR materials corresponds to Ecoinvent, while the

LCI database for the recycling of PCR materials corresponds to Ecosystem. Table 10 lists the specific database names and coefficients.

$$\begin{aligned}&\text{GHG}\ \textit{emissions from discharge activities}\\&= \textit{Product production volume from discharge activities} \times \textit{Emission factor}\end{aligned} \tag{3}$$

Table 10. Database of primary and secondary plastic production.

Database	Emission Factor ($kg\ CO_2$-eq./kg)	Location
crylonitrile-butadiene-styrene copolymer production	4.5624	Europe
polypropylene production, granulate	1.9003	
polystyrene production, general purpose	3.6747	
Material production, Recycled plastic from WEEE rABS, granulates; From WEEE collection to plastic granulates; In the context of French WEEE take-back schemes and European regeneration	0.5413	Europe
Material production, Recycled plastic from WEEE rPP, granulates; From WEEE collection to plastic granulates; In the context of French WEEE take-back schemes and European regeneration	0.421	
Material production, Recycled plastic from WEEE rPS, granulates; From WEEE collection to plastic granulates; In the context of French WEEE take-back schemes and European regeneration	0.591	

For example, considering the values in Figure 7, the production of electrical and electronic products requires 54,647 tons of virgin ABS. This results in GHG emissions of 249,324 tons CO_2-eq., calculated by multiplying the ABS production emission factor of 4.5624 kg CO_2-eq./kg of virgin ABS according to the ABS production quantity. Figure 8 presents the greenhouse gas emissions associated with producing virgin PCR and recycled PCR materials using the same approach. Approximately 363,101 tons of CO_2-eq. are emitted during the manufacture of virgin PCR for electrical and electronic products. Approximately 39,761 tons CO_2-eq. are emitted by transforming plastic generated from waste electrical and electronic products into recycled materials that can be supplied to manufacturers.

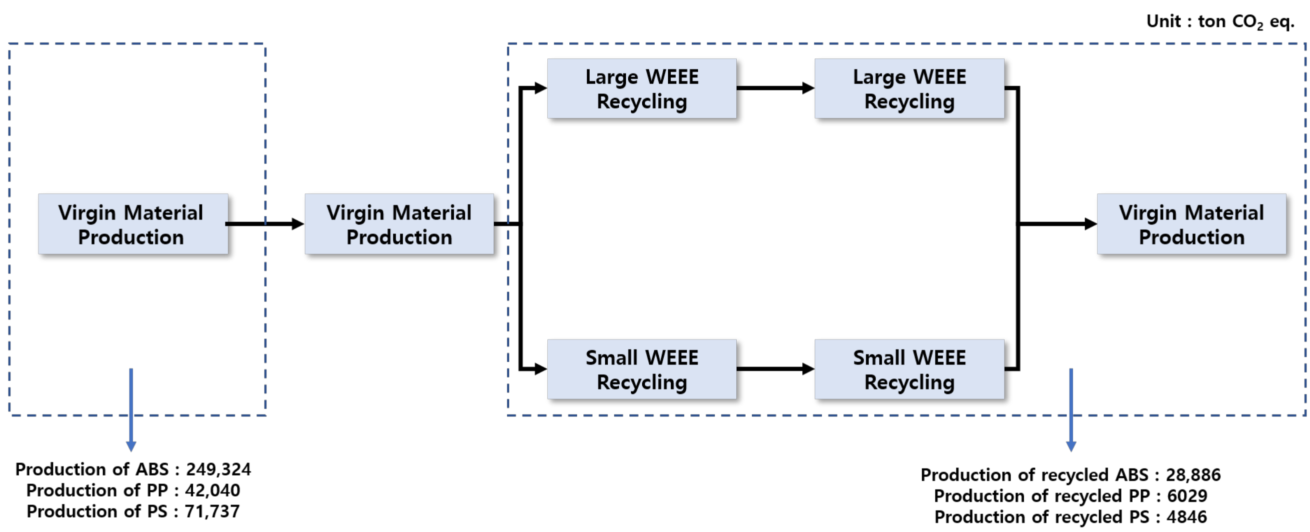

Figure 8. GHG emission from the production of virgin PCR and recycled PCR materials.

Figure 9 shows the GHG avoidance effect of recycled plastic production compared with virgin production based on the substitution rate of recycled PCR, in Figure 7, and the GHG emissions associated with PCR material production, in Figure 8. At the current recycling level, recycled plastic production can achieve a GHG reduction effect of 262,033 tons CO_2-eq., corresponding to a 72% reduction compared with the emissions from virgin production.

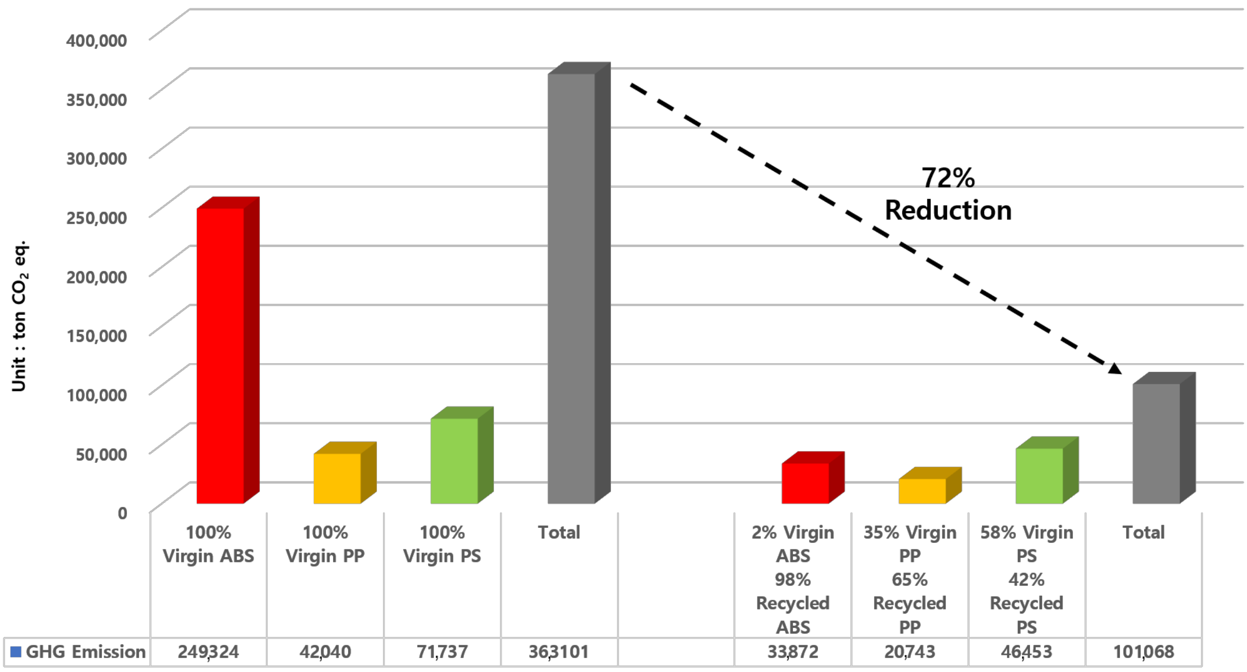

Figure 9. GHG reduction through recycled plastic.

4. Conclusions

The following conclusions were drawn regarding the recycling of plastics from waste electrical and electronic equipment in the jurisdiction in 2021 based on the survey conducted on one large-scale and one medium-/small-scale recycling facility, according to the domestic Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles (Environmental Assurance System):

First, ABS, PP, and PS are recyclable plastics generated from large-scale waste electrical and electronic equipment, estimated at 32,020, 8591, and 4920 tons, respectively. For medium-/small-scale waste electrical and electronic equipment, the recyclable plastics include ABS, PP, and PS, estimated at 21,343, 5729, and 3279 tons, respectively. Therefore, although the total amount of plastics in electrical and electronic products is 130,118 tons, only approximately 58% (75,882 tons) can be recycled and used as regenerated plastics. The data were considered an essential reference for future domestic policies related to recycled plastics based on actual information from domestic recycling sites. Various strategies and policy support will be needed to increase the proportion of recycled plastics available compared with the amount of plastic generated (130,118 tons) and improve resource circulation.

Second, most plastics generated from large-scale WEEE consist of single-material plastics without additives. On the other hand, for plastics generated from medium-/small-scale WEEE, there is a significant variation in properties (such as elongation, impact strength, and melt index) depending on the production date and lot because of the presence of additives used to enhance the material properties. Therefore, research is needed to standardize the properties, manage additives and hazardous substances, and expand recycled plastic use.

Third, for small household appliances, ABS and PS exhibit some property variations. In the case of PS used in small household appliances, the content of Br is high, making it difficult to apply in electrical appliances. Furthermore, PP in small household appliances contains a high concentration of composites or GF (glass fibers). Among the samples tested, only ABS was suitable for application in electrical appliances.

Fourth, regarding the recycled plastics generated from waste electrical and electronic equipment, their properties are limited to following the properties of virgin materials used in electrical and electronic products. Therefore, the most suitable recycling method is closed-loop recycling, which supplies recycled plastics for producing new electrical and electronic products.

Fifth, an analysis of the greenhouse gas mitigation effect based on closed-loop recycling confirmed that using recycled materials for production could reduce greenhouse gas emissions by 72% compared with producing electrical and electronic products using 100% virgin materials. On the other hand, secondary data were used to calculate the reduction in GHG emissions in this study, leading to limitations in geographical, temporal, and technological boundaries. To increase the accuracy, further research will be needed using the primary data from actual investigations. For an advanced LCA study, it is anticipated that scenario-based prospective methods can also be employed beyond a simple analysis of existing environmental impacts [8,42].

Finally, the results derived from this research project will provide fundamental data for future European and domestic regulations, as mentioned in the eco-design and GR certification of the EU. Furthermore, these findings have significant value as important reference or fundamental data because the use of recycled plastics is expected to increase in the production of new products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16176358/s1, Table S1: Number of processing and the weight of small and medium-sized waste electrical and electronic products of M Company in 2021.

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ABSFR	Fiber-Reinforced ABS
ASTM	American Society for Testing Method
Br	Bromine
EPR	Extended Producer Responsibility
ErP	Energy-related Products
ESPR	Ecodesign for Sustainable Products Regulation
EuP	Energy-using Products
GF	Glass Fiber
GFPP	Glass Fiber Polypropylene
GHG	Greenhouse Gas
GPPS	General Purpose Polystyrene
GR	Good Recycled Product
GWP	Global Warming Potential
HIPP	High-Impact Polypropylene

IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
PA	Polyacrylate
PC	Polycarbonate
PCABS	PC and ABS
PCR	Post-Consumer Recycled
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
RoHS	Restriction of the use of Hazardous Substances in EEE
UL	Underwriter's Laboratories
WEEE	Waste Electrical and Electronic Equipment

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