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Greenhouse gas emission offsetting by refrigerant recovery from WEEE: A case study on a WEEE recycling plant in Korea

Jihwan Park[a,b,*], Insang Jung[a], Wonhee Choi[a], Sang Ok Choi[b,d], Sung Won Han[c]

[a] Research and Development Team, Korea Electronics Recycling Cooperative (KERC), 17 Daehak 4-ro, Suwon, 16226, Republic of Korea
[b] Program in Science & Technology Studies (STS), Korea University, 145 Anam-ro, Seongbuk-gu, Seoul, 02841, Republic of Korea
[c] School of Industrial Management Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul, 02841, Republic of Korea
[d] Department of Public Administration, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul, 02841, Republic of Korea

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ABSTRACT

The demand for new electrical and electronic equipment (EEE) has resulted in short replacement cycles for this equipment. This has led to the generation of a large amount of waste electrical and electronic equipment (WEEE). The proper disposal of WEEE is essential in order to manage greenhouse gas (GHG) emissions, as refrigerant injected EEE is a potential source of GHG emissions. In this study, carbon dioxide (CO_2) emissions from recycling activities that resulted in GHG emissions via refrigerant recovery were quantitatively evaluated. The evaluation was conducted based on the operational data from a WEEE recycling plant in 2016. To estimate CO_2 emission and offsetting effects, mass-balance and carbon-footprint analyses were conducted. The mass-balance data showed that 22,804 t of WEEE were recycled in a plant. The carbon-footprint analysis estimated that CO_2 emissions from all recycling activities, including all machinery and vehicles as well as fossil fuel and electricity use, reached approximately 4.097×10^3 tonne of CO_2 eq. Meanwhile, the CO_2 emissions prevented by the manual recovery of refrigerants (5186 kg) from WEEE accounted for approximately 2.877×10^4 tonne of CO_2 eq. These results, based on data from a recycling plant and showing an offset of CO_2 emissions by a factor of 7.02, demonstrate that refrigerant recovery could potentially reduce emissions by 2.467×10^4 tonne of CO_2 eq. per year. This study will demonstrate the optimal methodologies for estimating CO_2 emissions and offsetting, and inform environmental policy by providing an alternative approach to the problem of global warming.

1. Introduction

In the Republic of Korea, continued economic growth and consumer demand for new electrical and electronic equipment (EEE) has raised concerns about the environmental impact of its incineration and disposal in landfills (Lee et al., 2007; Jang, 2010; Park et al., 2018). Without properly managing the disposal of waste electrical and electronic equipment (WEEE), problems such as poisonous gases, contaminated water, and soil pollution can arise due to the various toxic materials contained in WEEE (Biganzoli et al., 2015; Duygan and Meylan, 2015; Bigum et al., 2017).

In Korea, the legal guidelines for recycling WEEE were based on the Extended Producer Responsibility (EPR) system, which was introduced in 2003. Based on this system, the Eco-Assurance (EcoAS) system was later introduced to improve eco-friendly design of EEE products and recycling rate of WEEE, in 2008. This was implemented to strengthen the obligations of manufactures and recyclers to design eco-friendly manufacturing and recycling processes (Jang, 2010; Manomaivibool and Ho, 2014). In 2014, the Target Management System (TMS) was introduced by applying the first target amount of 3.9 kg per capita in year (3.9 kg/cap yr) (Park et al., 2018). For the current year, the recycling target per capita is set at 6.0 kg/cap yr. It is highly probable that the recycling target will be announced over 8.0 kg/cap·yr in 2023. Because of these amendments to the national systems, the Korean Ministry of Environment (MOE) designated 10 items (large-sized home appliances) that were subject to recycling obligations in 2008 and 27 items (small and mid-sized home appliances) in 2014. This number will expand to 50 items in 2020 (MOE, 2018). Through the TMS, and the EPR and EcoAS systems, Korea achieved recycling results of 248,000 t in 2016 and 273,000 t in 2017. The MOE, the Korea Environment Corporation (KEC), and the Korea Electronics Recycling Cooperatives (KERC) are achieving quantitative recycling results. As a result, they are improving WEEE recycling in Korea.

In terms of environmental quality care, the management of

* Corresponding author at: Research and Development Team, Korea Electronics Recycling Cooperative (KERC), 17 Daehak 4-ro, Suwon, 16226, Republic of Korea.
E-mail address: jh.park@k-erc.or.kr (J. Park).

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greenhouse gas (GHG) emissions from WEEE is just as important as the correct disposal of WEEE. This is due to the various types of refrigerants within appliances such as refrigerators, air-conditioners, and water purifiers. GHG emissions can emanate from these sources as well as from the machinery that is powered by fossil fuels and used in their disposal and recycling. Due to system-boundary uncertainties caused by system design and measurement, it is difficult to precisely measure GHG emissions in the life span of WEEE (Bahers and Kim, 2018). To overcome this limitation, various analytical methodologies using carbon-footprint analysis and life-cycle assessment (LCA) have been applied to estimate the precise figure of GHG emissions within certain system boundaries (Gamberini et al., 2010; Hertwich and Roux, 2011; Krikke, 2011; Rocchetti et al., 2013).

In recent literature, carbon-footprint and LCA studies have evaluated the environmental impact of single items such as mobile phones, refrigerators, and televisions (Scharnhorst, 2006; Hischier and Baudin, 2010). In these studies, the evaluation of their environmental impact, including GHG emissions, was based on LCA scenarios, from the production of raw material through to final disposal. These scenarios used theoretical factors rather than actual empirical or experimental data for each stage, thus rendering them somewhat incomplete (Soo and Doolan, 2014). Many studies also concentrated on the reuse or recovery possibilities of specific metallic or non-metallic WEEE items without considering other types of waste such as wood (plasma display panels), urethanes (refrigerators), or funnel glass in cathode ray tubes (CRT) televisions (Wang and Xu, 2014). Indeed, many previous studies have estimated GHG emissions without analyzing the wide range of disparate data from manufacturers regarding the production and customer use of new products. However, manufacturers and sellers may not provide access to their production data, which results in uncertainty among researchers (den Boer et al., 2007; Muñoz et al., 2009; Ekener-petersen and Finnveden, 2013).

This study attempted to approach the evaluation of carbon footprints by concentrating on unit processes and narrowing the research scope so as to obtain actual data, rather than forcibly predicting inaccessible data. To accurately estimate WEEE GHG emissions, reliable data was gathered in order to match the mass balance between input and output within a certain system boundary (Hertwich and Roux, 2011; Xiao et al., 2016). In this study, WEEE GHG emissions were calculated based on the operational experiences of a recycling plant in Korea: the Metropolitan Electronic Recycling Center (MERC) (Park et al., 2018).

This study was conducted to estimate the impact of GHGs in terms of carbon dioxide (CO_2) emissions from the WEEE recycling process. The study was conducted in 2016 at MERC, a representative regional recycling center in Korea. We evaluated the quantity of CO_2 emissions prevented (i.e., carbon offset) by the WEEE refrigerant recovery process. Carbon offset means carbon reduction to compensate for carbon dioxide or GHG emitted in elsewhere (Goodward and Kelly, 2010). The results of this study, in terms of total CO_2 emissions and emission prevention, will contribute to the construction of a carbon-footprint profile for the Korean WEEE recycling industry. For example, analytical reports for carbon offsetting impacts based on the total amount of WEEE in formal sector can be utilized as an important evidence to attract WEEE, illegally treated without any refrigerant recovery process, from informal to formal sector. This study focused on the recycling stages of WEEE and its related transport. The environmental impacts of GHG emissions were evaluated, based on operational management data from MERC. Our case study is beneficial to the research field in the following ways: First, the plant used in this study recycles all 4 categories of WEEE (large-sized, mid-sized, small-sized, and telecommunication appliances) designated for mandatory recycling in Korea; second, the environmental impact of GHGs can be directly accounted for by using operational data from recycling and transport processes in recycling plant; and third, our predictions based on this data regarding the overall impact on global warming emphasize the importance of refrigerant recovery activity in WEEE. The system boundaries for the recycling processes carried out at MERC were selected because of their generation of reusable raw materials, such as ferrous and non-ferrous materials. According to the aforementioned system boundaries, the environmental impacts of GHG in final disposal plants, such as incinerators and landfills, were not included in this study, because MERC can be objectively and legally classified as a WEEE treatment plant (not the final disposal plant), according to the Wastes Control Act (KLRI, 2018a,b). Based on the criteria for treatment and final disposal plant from the Wastes Control Act, treatment plant can produce reusable resources through various recycling processes such as shredding, crushing, disassembling, compacting, and separating. At the same time, treatment plant discharges unrecyclable waste to final disposal plants for incineration and landfill.

2. Materials and methods

The research methodology comprised 4 steps: definition of system boundaries, mass balance, materials and inventory analysis, and impact assessment and interpretation. The system boundaries focused on the recycling stages of WEEE, including transport to and from the facility. The total amount of WEEE delivered to MERC was measured against the generation of reusable resources and the amount of waste transported to other facilities (Fig. 1).

2.1. System boundaries

The main purpose of this study is to estimate annual GHG emissions and evaluate GHG emission offset. These evaluations were conducted by recovering refrigerant using a carbon-footprint analysis during the WEEE recycling process at MERC in Korea. The study focused on certain stages of the life cycle of WEEE, ranging from transport to recycling to final transport. We calculated and evaluated the mass balance between the total amount of WEEE transported to MERC and, following the recycling process, the reusable resources and waste that were transported out of MERC. Our results provide an estimation of annual CO_2 emissions in the domestic WEEE recycling industry, taking into consideration the number of Korean recycling centers of similar size and their recycling capacity. Our results also emphasize the importance of the refrigerant recovery process, by both WEEE recycling plants and individual recyclers, for the prevention of refrigerant emissions.

The WEEE treatment-process can be divided into 5 stages: collection, transport to the recycling plant, recycling to generate reusable resources or waste, transport from the plant to secondary treatment or final disposal plants, and final disposal. Among these 5 stages, only 3 were applied as estimation factors for this study. The collection and final disposal stages were not included in the study, because it is very difficult and complex to obtain direct evidence data that can estimate carbon emissions for various types of WEEE collection activities and final disposal methods. In the system boundary of this research, 2 types of transport stages were included: (1) The transport of WEEE to the plant (MERC) for recycling, and (2) the transport of reusable resources and waste to secondary treatment or final disposal plants following handling. The recycling of WEEE consisted of 3 sub-stages: dismantling, shredding, and separating into component materials across item types, models, and manufacturers. The dismantling stage was mostly manual: First, workers removed all detachable components such as glass racks, printed circuit boards, and gaskets. Second, they extracted refrigerant (CFC-12, HCFC-22, and HFC-134a) from the appliances without detaching the compressor. The subsequent processes were automatic and included mechanical “shred or crush” and separation stages (Lee et al., 2007; Park et al., 2018). In the recycling stage, reusable resources were extracted, and 29 secondary raw materials and 8 types of waste were separated, as shown in Fig. 1. The data regarding GHG emissions and offsets for reusable resources and waste in the secondary treatment and final disposal stage were insufficient. Thus, this study focused on the

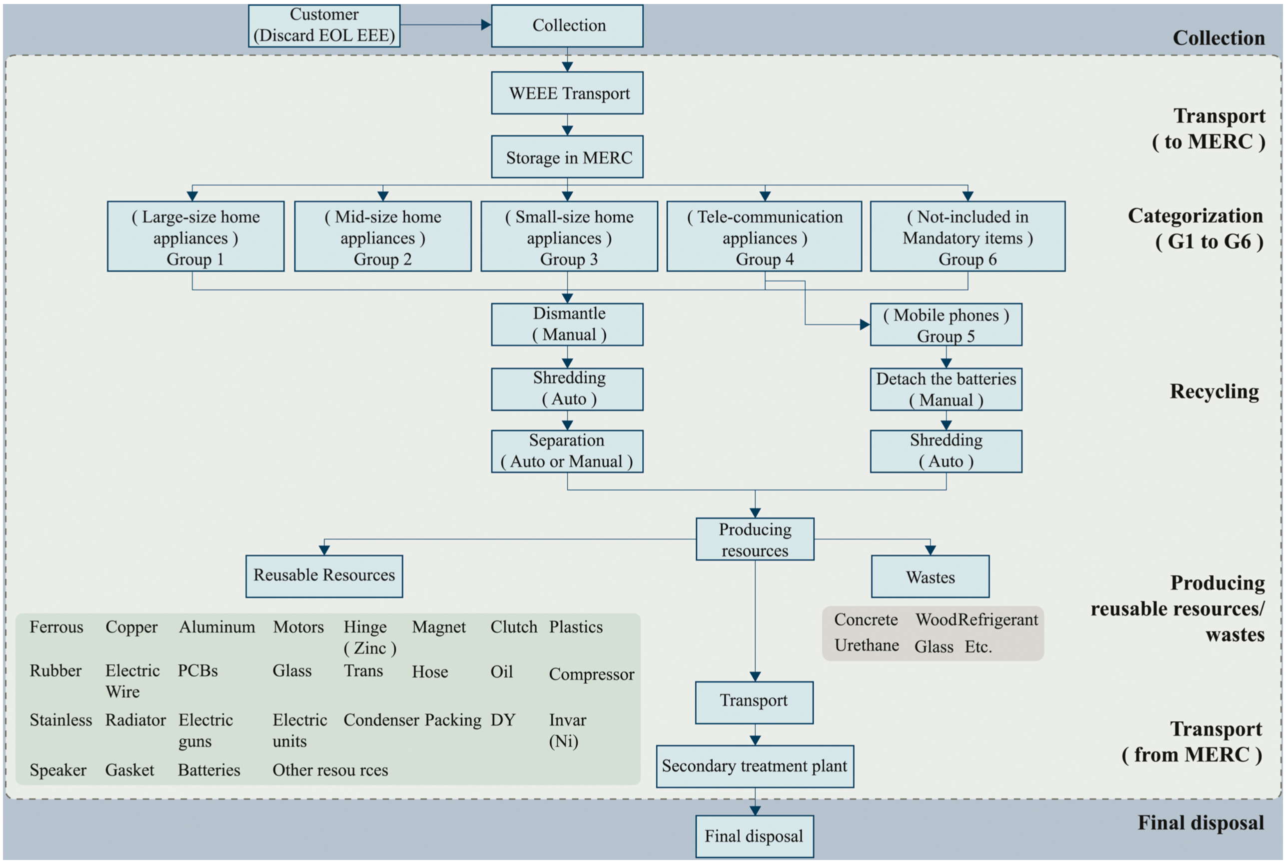

Fig. 1. Schematic system boundaries. The dotted box indicates the boundaries for estimating the target categories for GHG emissions and offsetting effects and several categories for analyzing the mass balance of WEEE and its derivatives for specific items.

transport and recycling stages within MERC.

2.2. Mass-balance analysis

Prior to the estimation of GHG emissions from WEEE recycling, a mass-balance analysis was conducted to improve estimation accuracy and confirm data reliability. The analysis was conducted by matching the total quantity and weight between input (WEEE) and output (reusable materials or waste), based on the information recorded in MERC. The results of a mass-balance analysis can contribute to the evaluation of both intensive and individual recycling results for 5 WEEE groups (including mobile phone), that legally required to recycle by the Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles (KLRI, 2018a,b). Table 1 categorizes the 6 groups and their specific items: large, mid-sized, and small home-appliances comprise groups 1 through 3 (G1–G3), respectively; home and office communication-devices, such as computers, copiers, facsimiles, and printers, comprise group 4 (G4); mobile phones and mobile phone batteries comprise group 5 (G5); and group 6 (G6) was composed of several items like electric plates, electric shavers, and massager not-included as ‘recycling mandatory’ list in Korea.

All inputs (WEEE) and outputs (reusable resources and waste) were categorized and analyzed using the mass-balance analysis, which measures units of ton (tonne). For the input materials, all WEEE in stock was cross-checked in terms of its quantity and weight, in a group or as an individual item (Hischier et al., 2005; Yang et al., 2008; Biganzoli et al., 2015). The quantity of WEEE is measured and managed by MERC and the transporter, and the weight of WEEE is measured by the weighing system, which is also managed by MERC. Furthermore, information regarding the quantity and weight of WEEE is reviewed by the KEC. Thus, numerical errors for various quantities and weights of WEEE will be corrected immediately if any abnormal data is detected. Similarly, the information regarding weight for reusable resources and waste is measured and managed by MERC, as shown in Table 1. The inputs were used to investigate the quantity and weight of each group, and the outputs were classified into 29 reusable resources and 8 forms of waste, as shown in Table 2. The mass balance is then calculated from this data. Certain reusable materials (e.g., wood, paper) and waste (e.g., glass fiber, glass wool) in comparatively small proportions were classified as “other resources” or “other waste.”

2.3. Material and inventory analysis

The material and inventory analysis were conducted using operational (quantitative) data from various WEEE recycling activities at MERC. The CO_2 emitted by MERC vehicles and machinery was calculated by converting the contributions of CO_2, methane (CH_4), and nitrous oxide (N_2O) energy into fuel and gas. Thus, the global warming potential (GWP) was calculated as follows:

$$CO_2\text{ eq} = Q \times \text{Emission Factors } (EC \times GWP), \quad (1)$$

where Q (in kilograms or liters) is the quantity of fuel or gas emitting GHGs and, thus, contributing to global warming. The emission factor is composed of 2 units: EC (J/kg) is the energy content of the fuel used in transport or recycling machinery, and GWP (kg CO_2 eq/J) is that fuel’s GWP. The GWP is calculated by aggregating the individual GWP of CO_2, CH_4, N_2O, and any synthetic gases emitted by the fuel used (Turner and Collins, 2013; Menikpura et al., 2014).

In Eq. (1), data from the Environmental Protection Agency (EPA) *Inventory of US Greenhouse Gas Emission and Sinks*, published in 2014, was used to calculate the emission factors (IPCC, 2006; Yang et al., 2016). Units of emission factors were converted from gallons to liters.

Table 1
Total amount of WEEE recycled at MERC (2016).

Recycling result (per year)	Categories for WEEE					
	[a]Large-sized [i]H.A. (G1)	[b]Mid-sized H.A. (G2)	[c]Small-sized H.A. (G3)	[d]Communication H.A. (G4)	[e]Mobile phone Phones (G5)	[f]Electric Items (G6)
[g]Amount recycled (units)	329,420	3562	25,469	8527	73,155	4193
[h]Weight (tonne)	22,418	85	124	112	7	58
Weight ratio (%)	98.30	0.37	0.54	0.50	0.03	0.26
Total weight (tonne)	22,804					

[a] G1: refrigerator, washing machine, air-conditioner, television, auto-vending machine (5 items).
[b] G2: food-waste disposal, electric oven, microwave, dish dryer (including dish washer), water purifier (5 items).
[c] G3: video player, air cleaner, humidifier, blender, fan, audio, water softener, rice cooker, iron, bidet, heater, vacuum cleaner (12 items).
[d] G4: computer, copy machine, facsimile, printer (4 items).
[e] G5: mobile phone including battery and charger.
[f] G6: electric items (e.g., electric pad, electric shaver, electric massager) were unspecified by law.
[g] Number of home appliances recycled in MERC.
[h] Number of appliances converted by average weight of each appliance (item).
[i] H.A.: Home Appliances.

Indirect CO_2 emissions related to electricity purchase and consumption were aggregated to calculate CO_2 emissions, based on quantity (kWh). This calculation includes other gases (CH_4 and N_2O) along with CO_2 (Turner and Collins, 2013). The calculation method was recommended by the EPA Greenhouse Gases Equivalencies calculator and the Australian National Greenhouse calculator (Table 3).

2.3.1. Transport

To carry out our analysis of the transport inventory, the transport paths were separated into 2 sections: The first path referred to the transport of WEEE to MERC from various collection points; the second path referred to the materials and waste transported from MERC to secondary treatment facilities. Thus, the transport paths were

Table 2
Reusable resources and waste generation through WEEE recycling at MERC.

Materials		Component rates in each group (%)					
		G1	G2	G3	G4	G5	G6
Reusable resources	Ferrous	50.04	42.92	17.17	10.25	5.50	19.28
	Copper	1.80	3.44	0.65	0.56	6.50	6.36
	Aluminum	3.94	3.25	1.04	0.20	7.60	8.50
	Motor	0.01	1.87	8.90	0.04	–	1.45
	Hinge	0.20	–	–	–	–	–
	Magnet	–	–	–	–	–	0.70
	Clutch	1.16	–	–	–	–	–
	ABS (plastic)	7.41	7.67	13.17	5.38	20.00	12.14
	PS (plastic)	2.13	–	11.46	5.40	7.00	1.42
	PP (plastic)	5.29	4.24	14.05	5.40	2.00	1.65
	PC/PE/PMMA (plastic)	0.55	0.93	0.82	–	–	2.53
	Other plastics	0.81	0.56	5.93	0.67	–	1.65
	Rubber	–	0.14	0.31	–	–	1.71
	Electric wire	0.34	0.74	2.13	0.24	–	1.43
	Printed Circuit Board	1.76	0.86	8.27	6.32	1.50	2.32
	Glass	7.15	4.79	0.04	0.02	15.20	10.38
	Transformer	2.07	4.63	4.57	0.08	–	0.60
	Hose	0.03	1.01	–	–	–	0.97
	Stainless steel	0.03	–	5.05	0.19	–	4.02
	Electric gun	0.07	–	–	–	–	–
	Electric unit	0.15	–	–	0.80	–	0.87
	DY coil (CRT)	0.04	–	–	0.80	–	–
	Invar (Nickel)	0.05	–	–	–	–	–
	Compressor	1.73	13.96	–	–	–	–
	Oil	0.22	–	–	–	–	–
	Speaker	–	–	3.37	0.02	–	–
	Gasket	0.20	0.09	–	–	–	–
	Battery	–	–	–	0.03	33.70	
	Other resources	0.17	1.80	1.70	3.14	–	1.96
Wastes	Refrigerant	0.16	0.02	–	–	–	–
	Front-glass (CRT)	1.88	–	–	34.32	–	–
	Back-glass (CRT)	0.98	–	–	18.66	–	–
	Concrete	0.66	–	–	–	–	1.39
	Urethane	7.36	–	–	–	–	–
	LCD panel	0.05	–	–	–	–	–
	Glass	0.11			2.92		6.64
	Other waste	1.45	7.08	1.37	4.56	1.00	12.03
Total (%)		100.00	100.00	100.00	100.00	100.00	100.00

Table 3
Emission factors based on various types of energy (fuel) sources.

Energy (fuel) source	Emission factor information	
	[a]Emission factor (EC × GWP)	Unit
Diesel	2.68	kg CO_2 eq/L
Gasoline	2.31	
Liquid petroleum gas (LPG)	1.54	
Lubricating oil	2.81	
Grease	2.77	
Electricity	1.35	kg CO_2 eq/kWh

[a] Included net effects of CO_2 (1), CH_4 (25), and N_2O (298) considering 100-year GWP, respectively.

Table 4
Data for estimating carbon emissions in transportation from WEEE collection points to MERC: Distance, rate, unit, and weight based on 2 pathways (take back and local government).

	WEEE transportation				
	Collection points	[a]Distance (km)	Rate (%)	Unit (ea)	Weight (tonne)
Take back (warehouse)	TB-A1	84.9	2.3	7276	373
	TB-A2	36.1	3.0	9491	487
	TB-B1	202.4	10.6	33,534	1721
	TB-B2	26.0	30.5	96,489	4952
	TB-C1	202.0	2.8	8858	455
	TB-C2	69.6	3.0	9491	487
	TB-C3	39.3	4.3	13,603	698
	TB-D1	203.1	6.7	21,196	1088
	TB-D2	37.0	12.6	39,861	2046
	TB-D3	7.3	10.5	33,218	1705
	TB-D4	73.0	7.3	23,094	1186
	TB-E1	101.6	2.3	7276	374
	TB-E2	77.6	1.7	5378	276
	TB-E3	43.3	2.4	7594	389
	Total		100.0	316,359	16,237
Local government (repository)	Gov-A	59.8	4.7	6031	310
	Gov-B	32.2	1.3	1646	85
	Gov-C	78.4	9.8	12,569	645
	Gov-D	11.1	2.1	2708	139
	Gov-E	59.8	2.7	3415	176
	Gov-F	196.9	25.8	32,953	1691
	Gov-G	88.9	20.5	26,261	1347
	Gov-H	120.6	5.4	6862	353
	Gov-I	92.7	1.3	1723	88
	Gov-J	27.7	1.4	1754	89
	Others	76.8	25.0	32,045	1644
	Total		100.0	127,967	6567

[a] 1-way distance.

separately classified according to their transport materials. The paths required different types of trucks and transport distances, and the loads were of different volumes and weights. In the WEEE transport category, analytical factors such as distance, rate, unit, and weight were all utilized as important factors in calculating CO_2 emissions. However, since WEEE recycling outputs could not be expressed as individual quantities, the distance, rate, and weight in this section are given without per-unit information (Table 4).

There are 2 types of WEEE collection points: 1 type is a warehouse facility where manufactures and sellers of EEE store their WEEE before it is transported to a recycling plant; another type is a regional depository, which is owned and operated by the local government or KERC. Here, WEEE is collected by a door-to-door service and brought to the depository prior to being transported to the recycling plant. This information can be used to explain current WEEE collection routes in Korea. The quantity of WEEE stored in the manufactures or sellers' warehouses is collected by a "take back" system when manufacturers or sellers are delivering a new product. The WEEE stored in local government depositories is also collected. KERC provides a free WEEE pick-up service nationwide; collecting activities are also carried out by local authorities on a periodical basis.

The number of warehouses and their transport data are expressed alongside the specific collection points and requisite analytical factors (i.e., distance, rate, unit, and weight) in Table 4. "TB" signifies "take back" (where WEEE is collected from warehouses); letters A through E signify a manufacturer or seller; and numbers 1 through 4 designate the number of warehouses belonging to specific manufacturers or sellers who transport WEEE to MERC. "Gov" signifies the local depositories who are involved in the WEEE door-to-door system (operated by KERC) and periodic collection activities (operated by local authorities); letters A through J signify major WEEE collection points (depositories), and "others" represent very small local depositories where fewer amounts of WEEE are collected. Here, the alphabetical order signifying for manufactures, seller, local depositories was randomly designated.

Following processing, reusable resources and waste generated in MERC go to secondary treatment facilities or disposal sites. The recycled raw materials are transported to the secondary treatment facility, where the outputs can be used in the manufacturing of new EEE or another products. The waste is taken to an incinerator or landfill, as it cannot be reused. In Table 5, "Re" indicates transport to the secondary treatment plant, with letters A through O indicating secondary plants located throughout Korea. "Waste" represents the transport of waste derived from MERC processing, with letters A through H indicating particular secondary treatment plant or final disposal plant. The total amounts of each transport type (reusable or waste) are shown at the bottom of Table 5.

The measurements of 2.5, 5.0, or 11.0 t indicate the sizes of the trucks used to transport WEEE to MERC and to transport reusable resources and waste from MERC to secondary treatment and final disposal plants. The total GHG emissions of trucks during transportation was calculated by multiplying the amount of GHGs (CO_2, CH_4, N_2O) and emission factors, based on the inherent energy features of both vehicle fuel and GWP values. (This is under the assumption that the fuel was

Table 5
Data for estimating carbon emissions in transportation from MERC to secondary recycling plants: Distance, rate, and weight based on 2 pathways (recyclable materials and waste).

	Resources and waste transportation from MERC			
	Companies	[a]Distance (km)	Rate (%)	Weight (tonne)
Reusable resources	Re-A	61.2	32.7	7448
	Re-B	106.8	3.1	699
	Re-C	56.8	5.0	1144
	Re-D	34.1	1.0	225
	Re-E	34.3	0.9	198
	Re-F	90.4	3.7	848
	Re-G	57.0	7.9	1795
	Re-H	28.9	0.6	133
	Re-I	49.2	0.6	133
	Re-J	85.3	1.1	244
	Re-K	61.2	21.3	4860
	Re-L	53.9	0.2	51
	Re-M	18.8	0.1	22
	Re-N	12.9	1.2	277
	Re-O	192.6	0.6	146
	Total	943.4	79.9	18,223
Waste and others	Waste-A	58.7	2.2	495
	Waste-B	5.4	1.1	241
	Waste-C	6.3	0.1	25
	Waste-D	82.8	3.2	741
	Waste-E	63.8	1.8	403
	Waste-F	235.0	6.1	1381
	Waste-G	23.0	1.6	376
	Waste-H	64.5	4.0	919
	Total	539.4	20.1	4581

[a] 1-way distance.

Table 6
Transport emission factors, with different trucks and usage rates.

	Emission factors (kg/ton km)				Truck use rate (%)	
	CO_2	CH_4	N_2O	[a]CO_2 eq	[b]Stored in MERC	[c]Released from MERC
11.0 tonne (truck)	0.063019	0.00005742	0.00000019	0.0642821	72.55	39.54
5.0 tonne (truck)	0.091553	0.00008159	0.00000026	0.10011489	17.71	51.65
2.5 tonne (truck)	0.14562	0.00012994	0.00000042	0.14847856	9.74	8.81
Total	–	–	–	–	100	100

[a] Calculated by considering the GWP index for 3 major GHGs: CO_2, CH_4, NO_2.
[b] Indicated the rate of trucks used at the WEEE storage stage at MERC.
[c] Indicated the rate of trucks used at the reusable resources or waste stage at MERC.

fully combusted by the truck engine during use.) The specific emission factors for GHGs, described in Table 6, were determined based on the international guidelines set out in the *Fourth Assessment Report* (AR4), which was published by the Intergovernmental Panel on Climate Change (IPCC) in 2007 and the 2012 Australian National Greenhouse Accounts Factors (Song et al., 2018a,b; Turner and Collins, 2013). Emission factors from the trucks were calculated based on diesel fuel and classified according to truck volume, complying with the international guidelines for truck classification. Table 6 displays the emission factors in kilograms per ton-kilometer (kg/ton·km) and the usage ratios for each truck at the beginning and end of the journey.

2.3.2. WEEE recycling

To calculate the real-time GHG emissions during the WEEE recycling process, the emission type, content, fuel, and consumption amounts were investigated. MERC has a series of processing machinery, including but not limited to 5 mechanical crushing or shredding devices, 5 automatic sorting devices, 2 solid refuse fuel (SRF) producing facilities, and 2 bag filters to recycle 27 types of EEE items, as specified by the Korean Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles (Park et al., 2018; KLRI, 2018a,b).

According to the Greenhouse Gas Inventory Building Standard of IPCC, the GHG emission category, depending on the emission type and source, is divided into 2 subcategories: direct and indirect as shown in Table 7 (IPCC, 2006). Direct emissions were then divided into 4 subcategories: stationary combustion, mobile combustion, facility utilities, and refrigerant emission from EEEs (Table 7). The major fuels in the stationary and mobile-combustion categories were diesel, gasoline, and liquefied petroleum gas (LPG), and the most commonly emitted refrigerants were HFC-134a, CFC-12, and HCFC-22, along with CO_2 from EEEs and extinguishers (Nakano et al., 2007; Foelster et al., 2016). Meanwhile, indirect emissions were calculated from the plant's use of electric energy. To calculate the amount of GHGs generated by MERC in 2016, all emissions released during the recycling process were included.

3. Results

3.1. Recycling performance and mass balance

In 2016, 444,326 units (22,804 t) of WEEE (group G1–G6) were processed at MERC. The recycling proportions for each group showed that by weight, G1 was the highest at 98.3%, followed by G3 (0.54%), G4 (0.50%), G2 (0.37%), G6 (0.26%), and G5 (0.03%) (Table 1). Within G1, recycled refrigerators and air-conditioners made up 66.6% (14,923 t) and 1.9% (437 t) of WEEE, respectively. Other items in G1 included washing machines (25.8%), televisions (5.6%), and vending machines (0.1%). Meanwhile, water purifiers accounted for 57.0% (48 t) of WEEE in G2. All were successfully processed at MERC during the same period.

When conducting a mass-balance analysis of the inputs (WEEE) and outputs (reusable resources and waste) at MERC, various WEEE components and their usage ratios were calculated for each group. As detailed in Table 2, the reusables and waste from G1 were 87.3% and 12.7%, respectively. The percentage of reusable raw materials for this group was larger than for the others; this trend was not observed in G4 due to the inclusion of CRT televisions (52.9%). The mass-balance results for specific materials in the production of reusable raw materials illustrated several features for the various paths of reusables. The rates for ferrous materials in G1 (50.0%) and G2 (42.9%) were higher than for other groups, while the rates for plastics were higher in G3 (39.5%), G5 (29.0%), and G6 (19.4%). This difference can be accounted for due to the fact that G1 contains large-sized appliances constructed from ferrous-based frames, while other groups contain appliances constructed from various plastics.

3.2. Emission factors for fuel and electricity

Previous literature has investigated emission factors for CO_2, N_2O, and CH_4 in terms of the combustion of fossil fuel and electricity generation from power plants; thus, our present study implemented these emission factors to calculate the amount of GHGs in both the transport

Table 7
Major sources of GHG emissions from WEEE recycling in MERC (2016).

Category	Type	Content	Fuel	Chemical formula	Amount	Unit
Direct	Stationary combustion	Electricity generation (emergency)	Diesel	CO_2, CH_4, N_2O	30.0	Liter
		Boiler			7954.0	
	Mobile combustion	Fork lift			20,166.0	
		Vehicles (all employees)	Diesel, gasoline, LPG		3016.0	
		Vehicles (business)			1080.0	
	Supplies	Lubricating oil	Lubricating oil		35.0	
		Grease	Grease		12.0	
	Refrigerant omission	Extinguisher		CO_2	0.2	Kg
		Refrigerant (vehicles)		HFC-134a	0.5	
		Refrigerant (refrigerators)		HFC-134a, CFC-12	251.0	
		Refrigerant (air-conditioners)		HCFC-22, HFC-134a	8.8.0	
		Refrigerant (water purifiers)		HFC-134a, CFC-12	1.0	
Indirect	Electricity power	Various machineries	Electricity	CO_2, CH_4, N_2O	2,118,492	kWh

and WEEE recycling processes. In this study, 4 types of fossil fuels and electricity are considered to be major GHG-causing materials. Their emission factors, converted into kg CO_2 eq/L (fossil fuels) and kg CO_2 eq/kWh (electricity), are listed in Table 3. The fuel with the lowest emission factor per unit is LPG (1.54 kg CO_2 eq/L), while lubricating oil (2.81 kg CO_2 eq/L) is considered to have the greatest per-unit effect on global warming. The emission factor for electricity per unit (kWh) is 1.35 kg CO_2 eq/kWh.

The transport of WEEE, reusable resources, and waste necessitated a different method for estimating GHG emissions. During the transport of WEEE to MERC, the types of vehicles used (in order of preference) were 11.0-tonne trucks, 5.0-tonne trucks, and 2.5-tonne trucks, with usage (driving) percentages of 72.55%, 17.71%, and 9.74%, respectively. During the transport of reusable resources and waste from MERC, the preferences shifted: The 5.0-tonne truck (51.65%) was followed by the 11.0-tonne truck (39.54%), followed by the 2.5-tonne truck (8.81%). This shift is likely due to the fact that larger trucks are more efficient at transporting larger numbers of heavier appliances to the plant, while medium-sized carriers are more efficient at transporting down-sizing reusable resources and waste produced by recycling (Table 6).

3.3. GHG emissions

3.3.1. WEEE recycling

Based on IPCC reports for categorizing GHG emissions depending on direct or indirect emission production, both categories were investigated in the WEEE recycling process at MERC. As mentioned in Section 2.3.2, the direct emission types were stationary combustion, mobile combustion, facility emissions, and refrigerant emissions. Indirect emissions were restricted to electricity usage. The use of fossil fuels for emergency electricity generation and heating (boiler) was categorized as a direct emission from stationary combustion; that were 30 and 7954 L of diesel, respectively (Table 7). The records of use for vehicles directly related to operations within the recycling plant, such as commutes, business trips, and fork-lift use, were classified as direct emissions from mobile combustion. Fork-lifts used 20,166 L of diesel annually, and other vehicles used a combined 4096 L of diesel, gasoline, and LPGs. In the facility utilities category of direct emissions, the annual amounts of lubricating oil and grease used were 35 and 12 L, respectively. Finally, refrigerant emissions from extinguishers, vehicles, and WEEE were estimated by conducting interviews with the workers at MERC and experimental monitoring. It was discovered that the plant's refrigerant recovery process had a failure probability of approximately 5% due to lost compressors and refrigerant emissions during previous WEEE stages, such as transport. Taking into consideration the failure proportion of 5%, the amount of refrigerant emissions from refrigerators, air-conditioners, and water purifiers was 251 kg, 8.8 kg, and 1.0 kg, respectively. Indirect emissions in the form of electric power usage were 2,118,492 kW h for the year (Table 7).

The GHG emissions during the WEEE recycling process at MERC are shown in Table 8. The results were used to analyze the direct and indirect effects of these GHG emissions on the atmosphere. First, based on the category of direct emissions, which included whole emission types from stationary and mobile combustions, facility utilities, and refrigerant emissions, the actual or potential GHG emissions were measured against those of fossil fuels during the same 1-year period. Stationary combustion (boilers and emergency electricity generation) released approximately 2.132×10^1 and 8.000×10^{-3} tonne of CO_2 eq. for the year, respectively; 2 mobile combustion types (fork lifts and passenger vehicles) released 5.132×10^1 and 2.132×10^1 tonne of CO_2 eq., respectively. Facility utilities (grease and lubricating oil) released 1.300×10^{-1} tonne of CO_2 eq. The GHGs emitted from extinguishers, vehicles, refrigerators, air-conditioners, and water purifiers totaled approximately 855,800 t of CO_2 eq. Second, indirect emissions via electric power usage at the WEEE recycling plant released 2.860×10^3 tonne of CO_2 eq. in 2016, calculated from an electricity usage of 2,118,492 kW h for that year.

3.3.2. Transport

As mentioned in the methodology section, transport was calculated separately in terms of transporting WEEE to MERC and transporting reusable resources and waste from MERC to secondary treatment facilities, incinerators, or landfills. In their transport to MERC, end-of-life appliances were collected and transported from 14 warehouses operated by manufacturers and sellers and 10 regional depositories operated by municipal authorities and other local authorities. The total amount transported to MERC amounted to 22,804 t (444,326 units) across 6 item categories (G1–G6). Among them, 16,237 t (316,359 units) were successfully collected and transported in take back, and 6567 tons (127,967 units) were transported by KERC (door-to-door) and local authorities. The percentage for take back was 71.2%, and the percentage for the door-to-door system and collecting activities of local authorities was 28.8% (Table 4).

In relation to the transport from MERC, 2 groups left the facility for secondary treatment facilities or disposal. In total, 28 reusable raw materials were transported to 15 secondary or final treatment plants, and 7 types of waste were transported to 8 plants for incineration or landfill disposal (Tables 4 and 5). A total of 22,804 t of material was transported out of MERC in 2016, with reusable material amounting to 18,223 t (79.9%) and waste amounting to 4,581 t (20.1%). Based on annual recycling information, fossil fuel emissions factors (Table 3), truck usage by type of truck (Table 6), total amount of WEEE (Table 4), and total amount of reusable resources and waste transported (Table 5), a total of 2.972×10^2 tonne of CO_2 eq. was calculated as resulting from transport for 2016.

CO_2 emissions from the transport of WEEE (from collection points to MERC) and the transport of reusable resources and waste (from MERC to secondary treatment facilities) were calculated as 1.472×10^2 and 1.500×10^2 tonne of CO_2 eq. for the year, respectively (Table 8). Based on our mass-balance analysis, we assume the total mass of WEEE versus end products to be the same. The difference in CO_2 emissions, of only $2.800 \times 10^\circ$ tonne of CO_2 eq. per year, was likely incurred through variations in the type of transport vehicle (loading capacity) used and transport distance. For the transport of both WEEE and reusable resources and waste, CO_2 emissions from G1 were the highest; the percentage of CO_2 emissions of G1 in transport both to and from MERC was 98.3%.

3.4. Offsetting effects

At MERC, workers are required to recover injected refrigerant and detach compressors from refrigerators, air-conditioners, and electric water-purifiers prior to subjecting them to mechanical recycling processes. In 2016, a total of 5186 kg of refrigerant was successfully recovered at MERC. Among the 3 items mentioned above, the majority of refrigerants were recovered from refrigerators, at 5020 kg (96.2%), with 160 kg (3.1%) recovered from air-conditioners, and 36 kg (0.7%) from water purifiers. In terms of the types of refrigerants, the most-recovered refrigerant was HFC-134a at 2779 kg, followed by CFC-12 at 2242 kg, and HCFC-22 at 195 kg (Table 9).

The prevented CO_2 eq emissions were calculated in tonne by multiplying the volume and GWP index of each refrigerant recovered in MERC by its specific GWP value. The CFC-12 refrigerant, with 2242 kg recovered, prevented 2.444×10^4 tonne of CO_2 eq.; HFC-134a refrigerant, with 2779 kg recovered from refrigerators (G1) and water purifiers (G2), prevented 3.974×10^3 tonne of CO_2 eq.; and HCFC-22 refrigerant, with 195 kg recovered from air-conditioners (G1) and water purifiers (G2), prevented 3.530×10^2 tonne of CO_2 eq. for the year. This combined total weight of refrigerants recovered (5216 kg) from WEEE in 2016 prevented the emission of GHGs into the atmosphere that is equivalent to 2.877×10^4 tonne of CO_2 eq. (Fig. 2).

Table 8
Estimation results for annual CO_2 emissions and offsetting effects; CO_2 emissions were evaluated based on transport and recycling processes of WEEE.

Category	Type		Estimation of CO_2 emissions and offsetting effects (tonne CO_2 eq/yr)							
			G1	G2	G3	G4	G5	Etc.	Sum	Total
CO_2 emission	Transport	In	144.698	0.545	0.795	0.736	0.044	0.383	147.200	4097.205
		Out	147.450	0.555	0.810	0.750	0.045	0.390	150.000	
	Electricity generation (EM)		0.079	0.001	–	–	–	–	0.080	
	Boiler		20.954	0.079	0.115	0.107	0.006	0.055	21.317	
	Fork lift		53.126	0.200	0.292	0.270	0.016	0.141	54.045	
	Vehicle		8.525	0.032	0.047	0.043	0.003	0.023	8.672	
	Lubricating oil and grease		0.129	–	0.001	0.001	–	–	0.132	
	Refrigerant omission		841.246	3.166	4.621	4.279	0.257	2.225	855.795	
	Electricity		2811.345	10.582	15.444	14.300	0.858	7.436	2859.964	
Offset effects	Refrigerant recovery	CFC-12	24437.800							28764.720
		HCFC-22	298.650	54.300						
		HFC-134a	3965.390	8.580						

Table 9
Amount of refrigerant recovered from WEEE in MERC (2016).

Group	Items	Refrigerant types and amount recovered (kg)		
		CFC-12 ([a]GWP: 10,900)	HCFC-22 (1810)	HFC-134a (1430)
G1	Refrigerators	2242	5	2,773
	Air-conditioners		160	
G2	Water purifiers		30	6
Total		2242	165	2779

[a] Global warming potential.

4. Discussion

4.1. Refrigerant recovery and offsetting impact

Based on the Act on the Resource Circulation of Electrical and Electronic Equipment and Vehicles (KLRI, 2018a,b), all recycling plants should recover residual refrigerant in WEEE. Due to this law, and combined with the managerial activity of MOE (with KEC and KERC), the majority of recycling centers in the formal sector, including MERC, are aware of the importance of refrigerant recovery. The above law has stated the standards for pressure at refrigerant recovery machines, the principles of separation by refrigerant types, and the physical and chemical properties of pressure vessels. However, the guidelines for detaching method or work flow the compressor in the refrigerant recovery process are not mentioned. Most recycling plants have adopted a procedure in which the refrigerant is first recovered and then the compressor is separated from the main body (Xiao et al., 2016; Foelster et al., 2016). This process for refrigerant recovery was very important for MERC. If the compressor is removed before the refrigerant is recovered, a small amount of GHG is emitted into the atmosphere. In MERC, the workers detached all of the compressors after confirming that the refrigerant was fully extracted from the appliances (Lee et al., 2007; Park et al., 2018).

4.2. Key factors for GHG emission and offsetting

The rate of GHG emitted in the WEEE recycling process accounts for 92.75% of total emissions, and the GHG in the transport process accounted for only 7.25% of total GHG emissions across all transport types (WEEE or resources and waste). The percentages were not

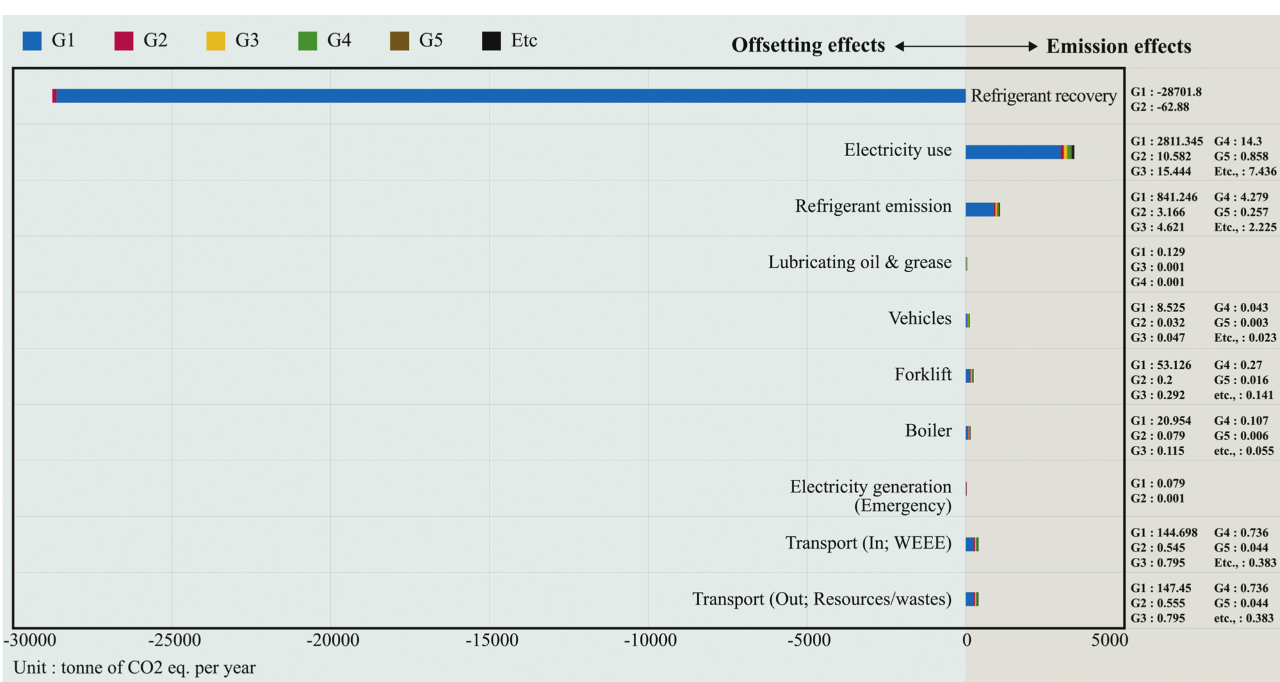

Fig. 2. Summary of CO_2 emissions and offsetting effects. This is based on the specific emission or offsetting sources within WEEE categories at MERC in 2016.

significantly different (WEEE: 49.53%, resources and waste: 50.47%). However, the emission rates depending on utility types were significantly different were significantly different: Electricity (69.80%) occupied the highest rate of GHG emissions, followed by refrigerant omission (20.89%), fork lifts (1.32%), boilers (0.52%), and vehicles (0.21%). However, a key factor of GHG emission, according to the WEEE grouping criteria, showed that G1 (98.3%) was the highest.

In the GHG offsetting stage, the refrigerant recovery was the only key factor for GHG offsetting. This result was similar to previous studies (Nakano et al., 2007; Biganzoli et al., 2015). However, depending on the type and quantity recovered in terms of the 3 types of refrigerants in the WEEE recycling process, GHG reduction varies. The highest contributing refrigerant type was CFC-12, which accounted for 85.12% of the total offsetting effect, based on the amount of CO_2 released. This was followed by HFCF-134a (13.84%) and HCFC-22 (1.04%). However, in terms of the actual recovered amounts, HCFC-134a (53.59%) was the most abundant, followed by CFC-12 (42.23%), and HCFC-22 (3.18%). This indicated that the influence of GHG offsetting can vary greatly, depending on the inherent GWP of the refrigerant. In this study, the recovery of CFC-12 was the most influential factor.

4.3. Limitations and further study

This study focused on the estimation of GHG emissions and offsetting through WEEE transport and recycling activities in a recycling plant (MERC). However, as of 2016, MERC's recycling volume was approximately 8.05% (22,804 t per year) of the total volume of 271,000 t of WEEE that is managed in Korea. In other words, additional information for the remaining 91.95% is needed so that a comprehensive study of the offsetting impact of GHG in waste recycling in Korea can be studied. Limitations exist not only in the formal sector but also in the informal (illegally managed) sector. In fact, 300,000 t of WEEE outside of the legally managed volume have been illegally handled in Korea (Lee et al., 2015). Strategies or methodologies for estimating GHG emission and offsetting in the informal sector were not used in this study due to lack of data.

Another limitation of this study was a lack of access to LCA analysis for WEEE due to restricted system boundary settings. As mentioned in Section 1 (Introduction), the system boundary for this study comprised the transport and recycling of WEEE and the transport of reusable resources and waste to the disposal plant. Therefore, energy consumption during the final disposal processes was not observed or considered in this study. In addition, energy savings, through the replacement of virgin materials, were not considered.

Despite these limitations, this study can pave the way for further investigation and analysis. This paper studied only 8.05% of the WEEE that is legally managed in Korea. However, this can be converted to 22,804 t per year, implying that the volume of WEEE studied is large when compared to previous literature (Rocchetti et al., 2013; Scharnhorst, 2006). Apart from MERC, 10 recycling plants, with capacities similar to that of MERC, have been legally operating in Korea (Park et al., 2018). We intend to expand the research area and scale of this study by targeting the remaining plants in order to analyze and observe GHG emissions and offsetting impacts in the Korean WEEE recycling field.

Based on the annual operating data of MERC, the analysis is based on actual data for all GHG emission and offset factors. This increases the reliability of the study and minimizes assumptions. Thus, the system boundaries have been reduced, but the reliability of the data has increased. As a result, the findings of this study can be used to evidence the need for the establishment of a GHG reduction strategy in Korea. The results are based on real data, and this lends credence to the study for policy-makers. This study also highlighted the importance of WEEE recycling in the formal sector: The GHG offsetting effects of recovering refrigerant from WEEE was 7.02 times greater than MERC's total GHG emissions.

The authors explained that this study could provide evidence of policy decisions that could attract WEEE from the informal sector to the formal one. However, this description does not discuss the WEEE collection and recycling process of the entire informal sector and instead focuses on an illegal aspect, that is, the intentional release of refrigerants to the atmosphere. In fact, it is clear that the informal sector is an important channel for WEEE collection and recycling in Korea. Thus, the Korea MOE needs to develop a policy that ensures proper recovery and disposal of waste refrigerants generated from the informal sector.

The authors suggest that Korea's MOE establish a system that provides private businesses in the informal sector with economic incentives, such as free supply of low-cost refrigerant recovery machines and subsidy for submission of refrigerant recovery task results to the MOE. For example, the Environment Ministry can expand the application range of the "carbon point system (Carbon Point System, 2018)," which provides incentives to businesses or homes with electricity, water, and gas savings. Then, private recyclers receive the incentives when they report or submit actual results of waste refrigerant recovery and transfer to final treatment plants (as the four above companies). This is a mere example, but it calls for careful consideration.

4.4. Refrigerant treatment system in Korea

Three types of refrigerants recovered from refrigerators, air conditioners, and water purifiers at MERC are handed over to final disposal plants by refrigerant type (CFC-12, HCFC-22, HFC-134a). The transferred refrigerants are finally treated either through reclamation (including refining process) or destruction (mainly through incineration) in final plants; as of November 2018, only four final plants for refrigerant treatment are legally registered with the Refrigerant Information Management System (RIMS, 2018) of the MOE.

Three of these plants, namely, Handam-technology Inc., Bumsuk Engineering. (http://www.bseng21.com), and Sunjin-environment Inc. (http://www.sunjin-env.com), treat waste refrigerants using destruction methods (via plasma technology for Handam-tech Inc. and Bumsuk Engineering; via incineration technology for Sunjin-environment Inc.). Meanwhile, Oun-R2 tech Inc. (http://ounr2tech.com) treats refrigerants using a refinery and reclamation method to produce reusable refrigerants. The MOE approved the legal registration of these four plants. At present, from the government's perspective, the MOE acknowledges both destruction and regeneration methods as eco-friendly final treatment processes for waste refrigerants, and there is no discrimination between types of treatment in the registration process.

5. Conclusion

This study quantitatively estimated carbon dioxide emissions (tonne of CO_2 eq) and the prevention of GHG emissions in all WEEE recycling at the MERC recycling plant in Korea in 2016. In this study, we compared CO_2 emissions from recycling activities and preventative refrigerant recovery activities using mass-balance and carbon-footprint analyses. The results of our mass-balance analysis showed that a total of 444,326 units (22,804 t) of WEEE were recycled and successfully converted into reusable resources or waste in 2016. Specifically, refrigerators, washing machines, air-conditioners, televisions, and vending machines accounted for 98.3% of the total recycled volume. In the carbon- footprint analysis, results showed that CO_2 emissions from all recycling activities, including machinery, fossil fuel, and electricity usage, amounted to approximately 4.097×10^3 tonne of CO_2 eq. per year. However, refrigerant recovery, at a total of 5186 kg, was the equivalent to approximately 2.877×10^4 tonne of CO_2 eq. for the year, offsetting CO_2 emissions from the WEEE recycling plant by a factor of 7.02. From a policy standpoint, these results are meaningful in emphasizing the importance of refrigerant recovery activity. We also demonstrate that mass-balance and carbon-footprint analyses are effective methods for studying future quantifications of GHG emissions in the field of WEEE recycling in Korea.

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