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Recycling and Material Flow Analysis of End-of-Life Fluorescent Lamps in South Korea

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Abstract: Proper management and treatment of end-of-life fluorescent lamps with a toxic metal of mercury has attracted critical concern in the solid waste community. In this study, material flow analysis (MFA) and substance flow of mercury were performed on the lamps by life cycle in South Korea. It was found that, in 2020, approximately 2957 tons (or 27.9 million units) of end-of-life fluorescent lamps from households were collected and recycled by the recycling facilities in South Korea. Approximately 278 kg of mercury was recovered from the lamps and treated at the hazardous incineration facilities. Based on the results of dynamic flow analysis, the amount of fluorescent lamps to be retried is expected to continually decrease to be about 14.2 million units, which is estimated to be 23 kg of mercury. However, continued collection efforts on end-of-life fluorescent lamps owing to increasing demands for light-emitting diode lamps should be made from the perspectives of proper treatment of mercury as well as resource recovery. More detailed studies on other mercury-containing lamps (e.g., metal halogen lamps, high-pressure mercury lamps, and high-pressure sodium lamps) are warranted to determine mercury flows in waste streams for proper collection and treatment upon disposal.

Keywords: fluorescent lamp; mercury; MFA; EPR; LED lamp

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1. Introduction

A fluorescent lamp has a low weight mercury content and uses fluorescence of a phosphor coating to produce visible light. It consists of a glass tube filled with a mixture of argon and mercury vapor. Mercury-containing light lamps or bulbs, such as fluorescent lamps or tubes, compact fluorescent lamp (CFL), high-intensity discharge (HID) bulbs, and neon/argon lamps have been widely used for residential use, commercial (retail, office, hospitality, and leisure premises) and industrial applications, street lights, or the electric sign industry for lighting. The extensive use of fluorescent lamps with a longer life span and higher energy efficiency replaced incandescent bulbs used for households. Furthermore, along with continued technology development by the lighting industry, light-emitting diode (LED) lamps were introduced into the markets in the early 2010s to provide lighting when voltage is applied to negatively charged semiconductors embedded in a plastic capsule, causing electrons to combine and create a unit of light as photon. LED lamps are more energy-efficient, relatively expensive, and have longer lifespans than those of fluorescent lamps, resulting in a significant reduction in light maintenance and labor costs.

As many countries began to phase out incandescent lamps in the early 2010s and planned to eliminate fluorescent lamps with strengthened regulations in line with carbon neutrality and reduction of mercury use, it is expected that the penetration of LED lamps will come to significantly dominate in the lighting market in 2030 [1]. For instance, in 2018, EU member states voted to phase out inefficient compact fluorescent lamps and halogen lamps by 2021 in households, commercial and industrial sectors, and street lights [2].

According to the International Energy Agency (IEA), global LED sales reached more than 10 billion units, with a 46.5% penetration rate in the market in 2019 [3–5]. In 2030, it is estimated that the penetration rate of LED lamps by sales among light devices to be sold in the world would rapidly increase to 87.4%, while the share of fluorescent lamps is 12.5% in the same year [6].

Periodical maintenance of fluorescent lamps results in tremendous amounts of end-of-life fluorescent lamps to be disposed. In addition, as new LED lamps equipped with modern technology for a longer lifespan and energy savings come to the markets at an increasing growth rate, large amounts of end-of-life fluorescent lamps are expected to continually be generated in municipal solid waste streams in the coming years. During the collection and treatment of the lamps, mercury vapor retained in the fluorescent lamps may become of crucial environmental concern owing to potential emissions into the air. For example, when a lamp is broken or disposed of in a landfill or incinerator, mercury can be released to the air, soil, surface water, groundwater, and other material (e.g., particulate collected by air pollution control device, landfill leachate). Sharp glass shred arising from the breakage of the lamps can also cause an injury to humans upon improper handling. Thus, intentionally breaking or crushing lamps should be avoided because mercury can be released into the ambient environment and may pose a potential hazard to human health. When fluorescent lamps are unintendedly broken, they should be placed into a properly sealed box to avoid any possible release of mercury vapors [7]. Such waste may be considered hazardous waste and should be treated at hazardous waste treatment facilities. End-of-life fluorescent lamps should be properly collected and treated at waste recycling and treatment facilities. Although the lamps with mercury may be composed of only a small fraction by mass in the municipal solid waste streams, they may be the cause of a large amount of mercury, if the total volume of the cumulative end-of-life fluorescent lamps streams is considered [8]. Thus, the environmentally sound management of the lamps has been an issue of concern for solid waste communities.

Fluorescent lamps are typically composed of a variety of materials and elements, including glass, aluminum caps, plastics, and fluorescent powder composed of phosphorous compounds and rare earth metals [9,10]. The detailed material composition of the lamps may vary depending on the type, shape, size, manufactured year, and models of lamps. For example, a compact fluorescent lamp typically consists of a glass tube, fluorescent coating material and powder, mercury, a copper electrode, an aluminum cap, a tungsten electrode sealed in lead glass, and other elements (e.g., argon, krypton, copper) [11,12]. The main fractions of lamps generally include glass, plastic, aluminum caps, and fluorescent powder. Recycling of glass, plastics, and aluminum from the lamps is economically feasible by resource recovery when mercury is properly separated from the devices and stored for disposal. Thus, it is important for the lamp recycling facilities to build mercury separation and recovery processes by separating recyclable materials from the lamps with mercury before they sell them on the market.

To cope with mercury pollution and their potential impacts, many developed countries have been trying to establish environmentally sound recycling and management system for mercury-containing lamps [8]. For example, in the United States, mercury lamps are classified as household hazardous waste, which is managed by Federal and State laws, including Environmental Protection Agency (EPA) regulations codified in the 40 CFR 273 [13,14]. Generators of end-of-life fluorescent lamps must follow the requirements by the regulations, including safe storage in structurally sound packages marked with Universal Waste Lamps, Waste Lamps, or Used Lamps; maintenance of documentation; training of employees in proper handling and emergency procedures; and safe transportation to a treatment facility. New regulations under the Toxic Substances Control Act would require manufacturers to phase out fluorescent lamps to prevent mercury releases into the environment, jointly by the American Council for an Energy-Efficient Economy (ACEEE), the Appliance Standards Awareness Project (ASAP), and the Clean Lighting Coalition in 2022 [15,16].

In the EU, fluorescent lamps have been managed by the EU Waste Electrical and Electronic Equipment Directive (WEEE Directive 2012/19/EC) since 2007 [17]. In order to solve the fast-increasing waste stream of such products, the WEEE Directive sets the collection and recycling targets (e.g., kg per person per year) of WEEE, aiming to increase the amount of WEEE that is appropriately treated and reduce the amount that is disposed of in landfills. Many European countries have made efforts in establishing recycling and proper management such as the disassembly processes, shredding processes, and residue treatment of end-of-life fluorescent lamps with the concept of the extended producer responsibility (EPR) system under the WEEE Directive [18]. The European Association of collection and recycling organization for WEEE lamps and lighting reported that more than 250,000 tons of lamps or an equivalent of two billion lamp units were recycled throughout Europe in 2020 by the proactivity of the EPR and circular economy policies [19].

A number of studies have been conducted to examine recycling systems and processes of mercury lamps for waste management [11,20–28], while the recycling activities and statistics of fluorescent lamps are available, especially in the USA [20], Germany [21], Japan [22], Taiwan [11], Iran [23], China [24,25], and Kuwait [26]. Lee et al. (2015) presented the management of end-of-life fluorescent lamps by the producer responsibility recycling program, as well as the recycling and reprocessing and policies in Taiwan [11]. Alsanad et al. (2021) addressed the lack of awareness of the community regarding proper usage, disposal, and recycling of fluorescent lamps in Kuwait and emphasized the implementation of the take-bake programs of the lamps [26]. Viana et al. (2022) reviewed the environmental concerns and recycling perspectives highlighting mercury and rare earth elements in fluorescent lamps. The authors reported that many developing countries need to take measures to reduce the environmental impacts as a result of improper disposal of used fluorescent lamps [27]. Farias et al. (2020) presented the evaluation of the mobility of the potential risks to human health upon direct disposal of the lamps in soils [28]. There are still very limited studies regarding the substance flow of mercury in various waste materials and the quantitative flow of the lamps in solid waste streams and their recycling processes. The determination of the levels and flow of mercury from mercury-containing lamps from households is very important for solid waste communities to develop sustainable waste management for proper treatment and recycling. As discussed in the previous studies, such impacts on the environment and human health risks related to the disposal heavily depend on the proper collection, recycling, and management systems of end-of-life fluorescent lamps. There is still a lack of comprehensive management studies of fluorescent lamps from production, consumption, and collection to treatment from a product life cycle perspective. Quantitative mass flow and evaluation of such devices are required to promote a circular economy by establishing recycling, resource recovery, and treatment of the lamps. Very limited previous studies presented the static flow of the lamps from production to disposal. Furthermore, there is no dynamic material flow analysis of the lamps in the literature so far.

The aim of this paper was to present the overview of recycling management practices and material flow of end-of-life fluorescent lamps from households by EPR in South Korea. Especially, our study examined the generation, collection, and recycling practices for mercury-containing fluorescent lamps. Static and dynamic material flow analysis (MFA) and mercury flow of the lamps were examined to determine their mass flows by life cycle. Finally, future challenges and suggestions are discussed for environmentally sound and sustainable management of the lamps.

2. Materials and Methods

2.1. Data Aquisition and Methods

The methodology applied during this study includes data collected from four fluorescent lamp recycling facilities, statistical data analysis associated with imports and demands of fluorescent lamps, site visits to the fluorescent lamp recycling facilities with interviews and conversations, and a review of available literature and relevant previous studies. Data dealing with the amounts of fluorescent lamps that are imported and consumed by domestic markets were collected from the Korea Trade Statistics Promotion Institute (KTSPI) and Korea Statistical Information Service (KOSIS), while the recycled and disposal amounts of the lamps were obtained by the Korea Environment Corporation (KECO), Korea Lamp Recycling Corporation (KLRC), and Korea Ministry of Environment (Korea MOE). The KECO, a semi-governmental organization under the Korea MOE, operates the recycling system of lamps by extended producer responsibility (EPR) since 2004, while KLRC, as producer responsibility organization (PRO) that receives collection and recycling costs paid by lamp producers and importers, financially supports the lamp recycling industry and annually reports recycled amounts to the KECO. Interviews and conversation with officials from the Korea MOE, the KECO, and the KLRC, as well as experts from the lamp recycling industry, were conducted to discuss recent efforts and technical development associated with fluorescent lamp recycling and management.

2.2. Material Flow Analysis for Fluorescent Mercury Lamps: Static and Dynamic Flow

A material flow analysis (MFA) was performed to quantify the mass/resource flow and loss in a defined system, also facilitating data reconciliation in a well-defined space and time. In this study, material flow of fluorescent lamps and substance flow analysis for mercury were conducted by life cycle (i.e., production, use, generation, collection, recycling, and disposal stages). The target products of fluorescent lamps by the analyses include low-pressure discharge lamps (linear fluorescent lamp, circular fluorescent lamp, twin-tube fluorescent lamp, and compact fluorescent lamp with ballast) regulated by EPR system in South Korea. Relevant data were acquired by life cycle of lamps in order to conduct the MFA, as shown in Table 1. Collection data of used fluorescent lamps from households by local governments were gathered by the KLRC, which reports the collection and recycling data to the KECO by EPR. Resource recovery data (e.g., glass, plastics, aluminum, and mercury sorption by carbon filter) were obtained during the site visits to the lamp recycling facilities.

Table 1. Data collection and acquisition for material flow analysis for fluorescent lamps.

Life Cycle	Type of Data	References
Imports and Demands	Import/stocks of lamps	Korea Trade Statistics Promotion Institute, 2004~2021 [29]
	Domestic demands for lamps	Korea Environment Corporation, 2004~2021 [30]
Consumption and collection	The number of lamps put on the markets	Korea Statistical Information Service (KOSIS), 2021 [31]
	Lifespan of fluorescent lamps and retirement and stock of lamps in use at households	Korea Industry Standard Committee (KISC) [32]
	Collection rates of end-of-life lamps	Korea Lamp Recycling Corporation, 2022 [33]
Recycling	Recycled amount by recycling facilities	Korea Lamp Recycling Corporation, 2022 [33]
	Recycled parts recovered by recycling facilities	Korea Lamp Recycling Corporation, 2022 [33]
	Amount of phosphor and carbon filters treated by waste treatment facilities	Korea Lamp Recycling Corporation, 2022 [33]
Treatment and disposal	Incinerated amount	Korea Ministry of Environment
	Landfilled amount	Annual statistics of waste generation and treatment, (2004~2021) [34]

The system boundary for this study included from product manufacturing to recycling and waste disposal of fluorescent lamps. The temporal boundary for static material flow analysis (Static MFA) was set to as of 2020. Mercury contents in the lamps vary from 5 mg or less to up to 90 mg per lamp [25,35]. The average mercury content in fluorescent lamps was estimated by the following equation. This is based on average content of mercury in a fluorescent lamp (8.0 mg of mercury in a tube) and weighted collection average of each type of fluorescent lamp.

$$Hg_{ave} = P_{LFL} \times Hg_{LFL} + P_{cirFL} \times Hg_{cirFL} + P_{tFL} \times Hg_{tFL} + P_{CFL} \times Hg_{CFL}$$

where Hg_{ave} (mg of mercury per tube) is the average content in fluorescent lamps. P_{LFL}, P_{cirFL}, P_{tFL}, and P_{CFL} are each fraction occupied by linear fluorescent lamp (57.5%), circular fluorescent lamp (2.8%), twin-tube fluorescent lamp (29.7%), and compact fluorescent lamp (10.0%) by receiving at lamp recycling facilities, respectively, based on the survey in this study. Hg_{LFL} (10 mg), Hg_{cirFL} (10 mg), Hg_{tFL} (5 mg), and Hg_{CFL} (5 mg) are the assumed mercury content per linear fluorescent lamp, circular fluorescent lamp, twin-tube fluorescent lamp, and compact fluorescent lamp, respectively. MFA software STAN (2.6.801) was employed to analyze material flow and to display the quantitative flow of lamps [36].

Dynamic material flow analysis (dynamic MFA) was also performed to determine the mass flow of mercury in the lamps by 2030. The dynamic MFA is used to quantify past material flows, establish the material flow patterns, and apply the life spans of such products to these patterns in order to track the temporal changes in the mercury flows in the future. Based on lifespan data of fluorescent lamps available by product specifications and Korea Standards fluorescent lamps for general lighting service [32] and AC supplied electronic ballasts for fluorescent lamps [37], the lifespans ranged from approximately 9000 h to 19,000 h. With the assumption of 10 h daily use, the average lifespan was estimated to be 3.5 years (or 12,750 h). The lifespan distribution with an average lifespan was utilized to determine the mercury flow of the used fluorescent lamps between 2007 and 2030. The future demands for fluorescent lamps was predicted with the assumption of 17.5% decreased annual demand, which is calculated by the average reduction between 2017 and 2021. The average weight per lamp for MFA was assumed to be 150 g for 2007 through 2015, and 106 g for 2017 through 2020, provided by the KECO, although the weight of the lamps may vary, depending on their types and models [38].

3. Results and Discussion

3.1. Collection and Recycling System of End-of-Life Fluorescent Lamps by EPR in South Korea

3.1.1. EPR Regulations on Fluorescent Lamps' Management

In South Korea, fluorescent lamps have been managed by the EPR system under the Promotion Act on Savings and Recycling of Resources (often called "Recycling Act") since 2004. It has promoted their recycling by establishing a resource circulation system of packaging materials (e.g., carton pack, metal cans, glass bottles, plastic packaging materials, and others) and products (e.g., fluorescent lamps, battery, tires, and others). LED lamps will be included in the EPR system in the beginning of 2023. The Korea Ministry of Environment (Korea MOE) announces mandatory recycling rates for products subject to EPR annually. Producers who are classified by the volume and the amount of sales or import (i.e., approximately 0.9 million USD or 4 tons for manufacturers, 0.27 million USD or 1 ton for importers) should take responsibility for their products for collection and recycling by achieving the set recycling rates. Most producers assume EPR collectively through joining the producer responsibility organization (PRO) and contributing to their obligations through membership fees. Nevertheless, some producers may also establish individual EPR schemes, either by recycling their waste materials by the take-back system or through a waste management organization.

The annual mandatory recycling rate for fluorescent lamps is calculated by the amount of recycling of the lamps subject to EPR against the amount put on the market. Such a target rate is determined by the national government, based on market conditions for recycling and demands, recycling capacity, collection schemes, and economic circumstances. During this process, relevant stakeholders including the representatives from the government, producers, recycling industry, experts, and non-governmental organization are engaged. For example, the mandatory recycling rates for fluorescent lamps by EPR were 80.8% in 2019 and 90.0% in 2021 [39]. The actual recycling rate is calculated by the recycled amount of fluorescent lamps divided by the amount of lamps put on the market in a given year.

3.1.2. Recycling System of Fluorescent Lamps in South Korea

In order to effectively implement the EPR system, each stakeholder should play a role of collection, recycling, and treatment of fluorescent lamps by following the responsibility in each stage (production, collection, recycling, and treatment) based on the lamp recycling and treatment standards set by the Act. Figure 1 displays the current recycling and management system of fluorescent lamps by EPR in South Korea. The stakeholders (i.e., manufacturers and importers, local government, recycling facilities, producer responsibility organization, and households and consumers) involve the recycling and treatment system of the lamps. Local governments provide collection boxes for the used fluorescent lamps at designated residential areas and regularly collect lamps for transportation. Lamp transporters contracted with the Korea Lamp Recycling Corporation (KLRC) as PRO transfer the collected lamps to permitted lamp recycling facilities. Fluorescent lamp manufacturers and importers (or producers) contracted with the PRO financially support their lamp recycling by paying collection and recycling costs of the lamps to meet their recycling target rate. The lamp recycling facilities mechanically process end-of-life fluorescent lamps by reclaiming recyclable parts (e.g., aluminum, glass, and plastics) and by recovering mercury from the lamps. The lamp recycling facilities should follow the recycling methods and standards and properly recover mercury from the lamps to prevent any release to the environment. Mercury should be captured by proper treatment devices (e.g., activated carbon filters) for further mercury treatment to waste treatment and disposal facilities. Mercury-containing filters from the recycling process are classified as hazardous waste by the Recycling Act.

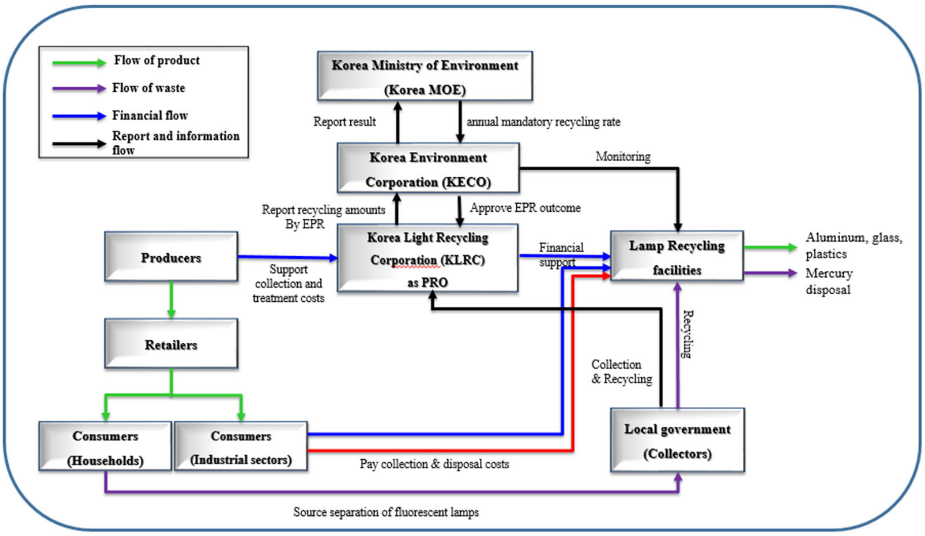

Figure 1. The recycling and management system of fluorescent lamps in South Korea.

Figure 2 displays the fluorescent lamp collection by source separation at households and transportation to the lamp recycling facility for resource recovery. Local governments collect the lamps from households and transport by permitted transporters contracted with KLRC to designated lamp recycling facilities.

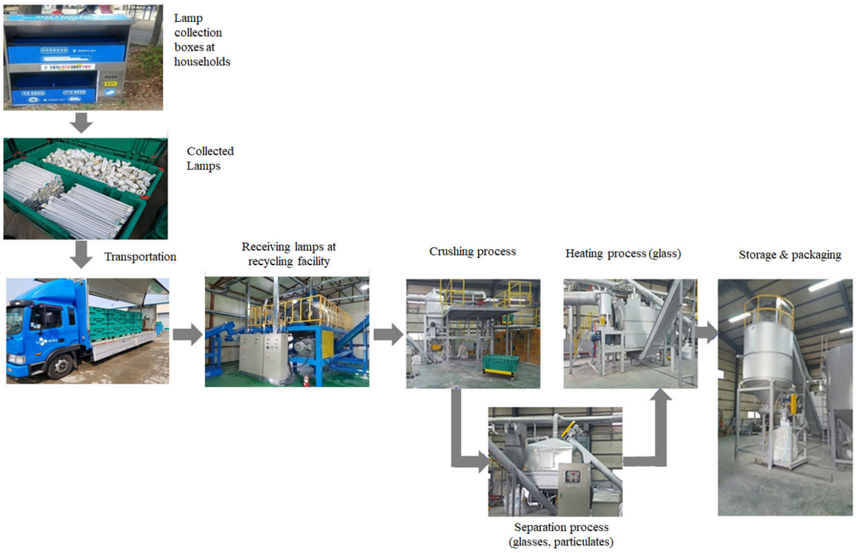

Figure 2. Collection, transportation, and recycling of end-of-life fluorescent lamps in South Korea.

3.1.3. Recycling Rates of Fluorescent Lamps by EPR

Figure 3 presents the domestic demands, actual recycled amounts, and mandatory recycling of fluorescent lamps between 2004 and 2021 in South Korea. The domestic sales over the period were relatively stable between 2004 and 2015, but they have been decreasing after 2015 from approximately 101.8 million units to 38.0 million units in 2021. The recycling rates have been relatively constant over the past decade, although the replacement of the significantly reduced demands for the fluorescent lamps with increased sales of LED lamps occurred in the period. The mandatory recycling rates by the EPR system were usually achieved by the producers owing to the active participation in source separation of end-of-life fluorescent lamps from households, the collection activities by local governments, and well-established lamp recycling facilities in the country supported by the EPR system. For example, in 2021, approximately 38 million units of fluorescent lamps were placed on the markets. The recycling target for the lamps in the same year by EPR was 95%, which was 36.1 million units. The actual recycled amount was 38.2 million units, which is equivalent to about 3600 tons of the used fluorescent lamps with an assumption of a standard weight of 106 g per lamp set by KECO.

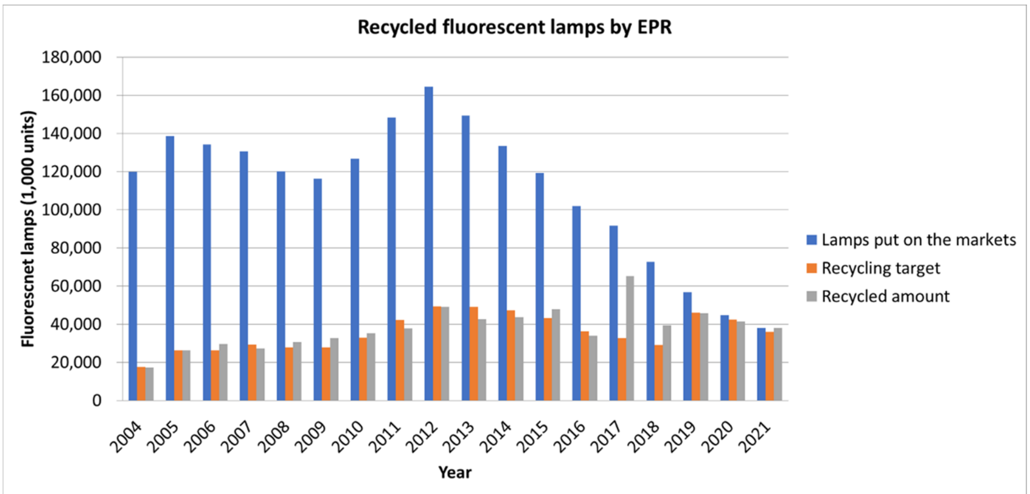

Figure 3. The recycling rates and mandatory recycling targets of end-of-life fluorescent lamps by EPR in South Korea between 2004 and 2021.

3.1.4. Recycling Process of Fluorescent Lamps' Waste

Figure 4 illustrates the recycling process at one of the lamp recycling facilities in South Korea. The end caps of linear fluorescent lamps are separated by cutting and other fluorescent lamps are mechanically crushed, followed by drum screens for particle size separation. Glass and plastics are recovered by the separation. The mercury-containing phosphor powder from all fluorescent lamps is collected by heating and cooling processes. Mercury in the vapor form from the phosphor powder is absorbed by activated carbon filter by condensation and treated at a hazardous waste incineration facility.

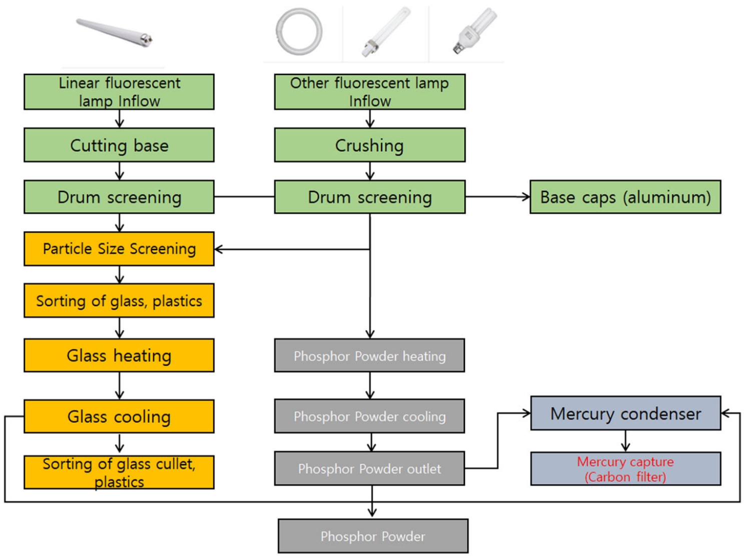

Figure 4. Recycling process of a fluorescent lamp recycling facility in South Korea.

3.2. MFA Result of Fluorescent Lamps by Life Cycle

Figure 5 illustrates the material flow of fluorescent lamps by life cycle in South Korea. As a result of the MFA study on fluorescent lamp manufacturers in Korea, it was found that fluorescent lamps are currently not manufactured in Korea owing to high manufacturing costs in recent years, heavily relying on imports from China (approximately 44.8 million units in 2020). The demand for the domestic market has been continually declining from more than 100 million units in 2016 to 38 million lamps in 2021. Approximately 27.9 million units (or 2957 tons) of end-of-life fluorescent lamps from households were collected and recycled, while 3.1 million units (328 tons) and 2.1 million units (223 tons) of the lamps were disposed of in incinerators and landfills, respectively. Glass (2371 tons), aluminum (80 tons), and plastic materials (166 tons), making up a large fraction of the lamps, were recovered by recycling processes and sold to the markets. Mercury sorbed in activated carbon filter as sorbents was treated at hazardous waste treatment facilities.

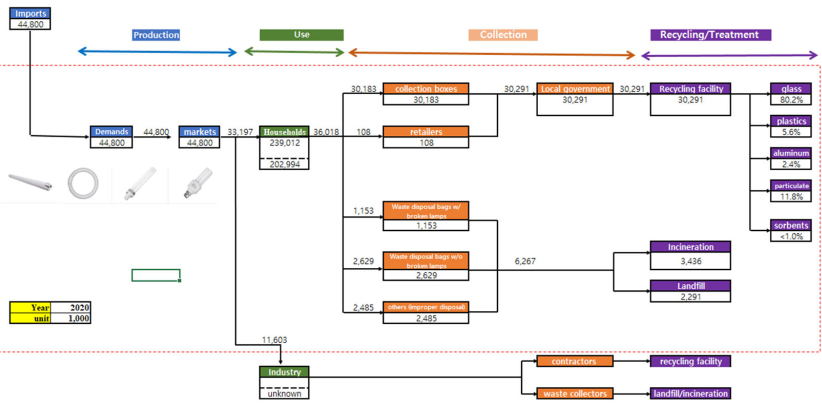

Figure 5. Material flow of fluorescent lamps by life cycle in South Korea (2020).

In China, a total of 7 billion fluorescent lamps were produced in 2011. Such lamps contained 29.3 tons of mercury. Much of the lamps are disposed of in landfills and incinerators, emitting mercury to the environment. The recycling rate for mercury treatment was found to be only less than 5% [25]. The recycling rates of the lamps for Canada, Japan, and the United States were also relatively low and reported to be approximately 7% [40], 9% [22], and 20% [41], respectively.

Figure 6 shows the substance flow of mercury in fluorescent lamps from households in South Korea. Much of the mercury present in the lamps flowed into the municipality collection system, followed by recycling processes. Based on the mercury flow of fluorescent lamps, approximately 166 kg of mercury in the products came into the household sectors. The amount of mercury stored in the lamps in households was estimated to be about 2233 kg. In 2020, approximately 332 kg of mercury in the used fluorescent lamps entered the recycling facilities by local government collections, while approximately 278 kg of mercury (83.7% of the total incoming recycling streams) was recovered by activated carbon filters during the recycling processes. The amounts of mercury treated at incinerators and disposed of in landfills were approximately 35 kg and 28 kg, respectively (Figure 4). Such disposal rates of mercury in fluorescent lamps were much lower than in the USA and China. In China, more than 15 tons of mercury were disposed of in landfills in 2011 [25]. According to the U.S. EPA, there were more than 2.7 billion fluorescent lamps in use in the United States in 2018, which contained between 12 and 15 tons of mercury [42,43]. In the same year, lamps containing more than 4 tons of mercury were disposed of; however, more than 75% of them were not recycled or safely disposed [44].

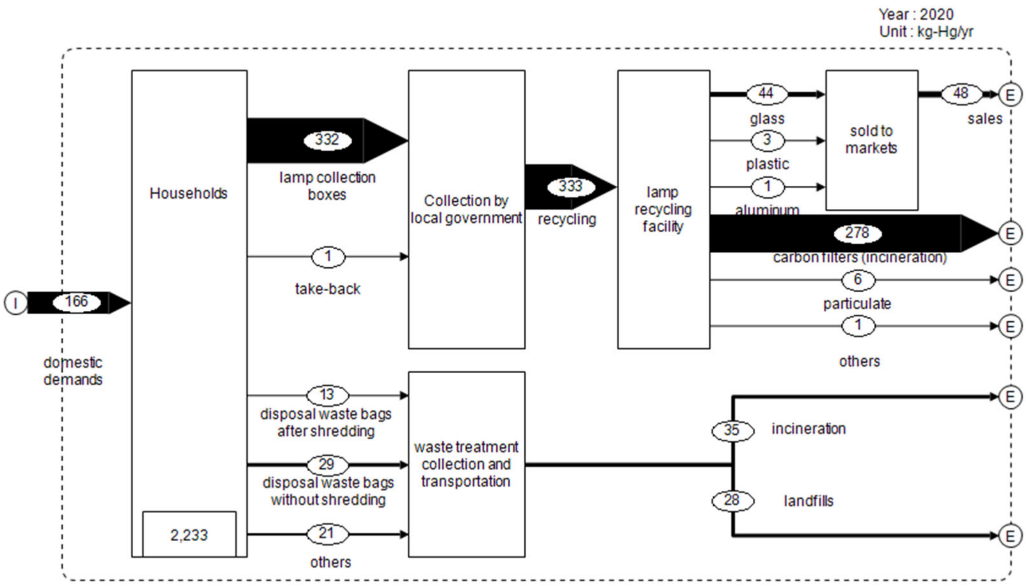

Figure 6. Mercury flow in fluorescent lamps from households in South Korea (2020).

3.3. Dynamic Flow of Mercury in End-of-Life Fluorescent Lamps

Figure 7 illustrates the dynamic flow of mercury in fluorescent lamps in South Korea between 2007 and 2030. After 2013, end-of-life fluorescent lamps have continually declined as a result of decreased demands by consumers with the replacement of LED lamps as well as strengthened regulations on mercury use in lamps by the Minamata Convention (e.g., not exceeding 5 mg mercury content per CFL for general lighting purposes that are ≤30 watts after year 2020). In 2021, the domestic demand for the lamps was approximately 38 million units, but in 2030, the demand is estimated to be 6.5 million units, which is a 83% reduction between the years. As a result, mercury flow in the lamps is also expected to continually decrease in the waste streams by 2030. In 2020, mercury flow in the waste stream was estimated to be approximately 390 kg in the generation of end-of-life fluorescent lamps.

However, based on the dynamic material flow analysis in this study, only 14 kg of mercury flow would be found in the waste lamp flow in 2030.

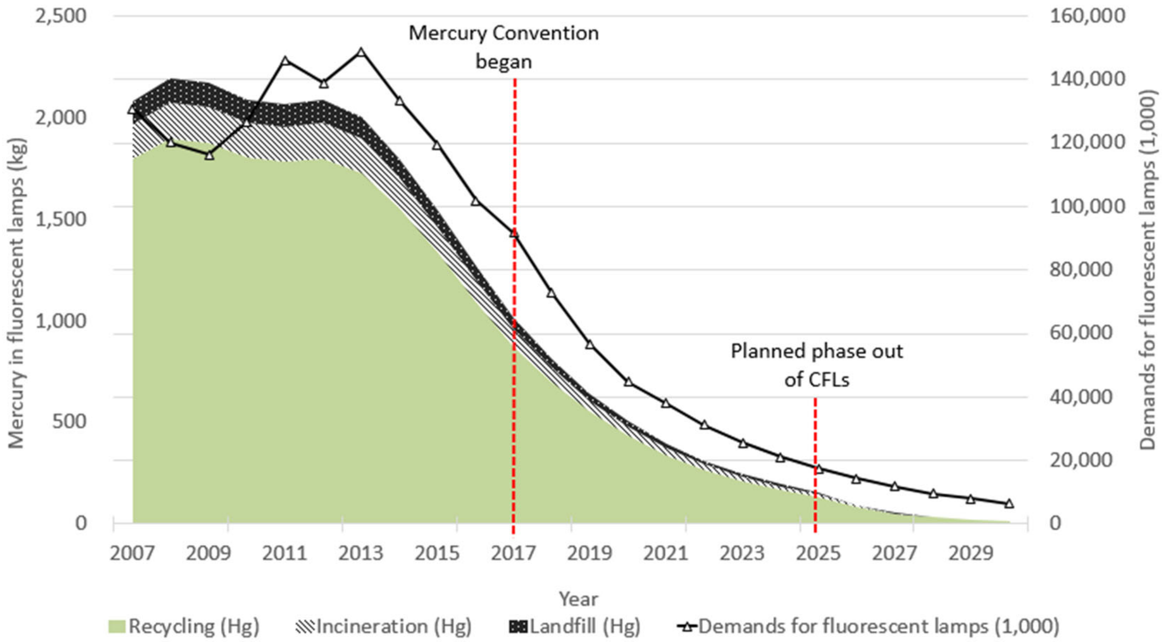

Figure 7. The result of dynamic flow of mercury in end-of-life fluorescent lamps in South Korea between 2007 and 2030.

4. Challenges and Suggestions

There have been successful collection and recycling systems of the used fluorescent lamps from households by EPR since 2004 in South Korea, by achieving the mandatory recycling rates assigned by the regulations. However, there are limited data and information on the collection and recycling of the lamps from industrial complexes and public sectors (e.g., industrial complexes, schools, office buildings, and so on). Further scientific studies are needed for determining mass flow and treatment of the lamps in the complexes, although many industry and public sectors have been replacing fluorescent lamps with LED lamps to save energy and electricity.

In addition, other types of lamps such as HID lamps (e.g., metal halogen lamps, high pressure mercury lamps, or high-pressure sodium lamps), often used for highway lamps, tunnels, sport complexes, parks, and street lights, should be properly collected and recycled after use. No detailed management practices and quantitative flows of such lamps are available so far. High-pressure sodium lamps, high-pressure mercury vapor lamps, mercury arc lamps, and arc-tube in ceramic metal-halide lamps often have a higher mercury content than those of fluorescent lamps, depending upon light output, light color, voltage and current, and size and types of manufacturers [15,45]. Thus, from the environmental perspective, sound management practices and guidelines should be established to prevent mercury emissions into the atmosphere and other environmental media (i.e., soils and water) upon disposal. Environmentally sound management practices of end-of-life lamps containing mercury were suggested by United Nations Environment Programme (UNEP), U.S. EPA, and Canada to provide guidance for their collection, storage, transportation, recycling, and disposal [35,46,47].

Current collection systems for lamps from households have focused on end-of-life fluorescent lamps, although a small quantity of end-of-life LED lamps are present and mixed in the fluorescent lamps. Manual sorting of LED lamps from the mixture is currently performed at the lamp recycling facilities. In the coming years, end-of-life LED lamps are expected to increase in the waste lamp flows. Thus, separated collection systems for the LED lamps from are required for effective recycling. More efforts to develop environmentally sound recycling and treatment technology of LED lamps along with mandatory recycling target rates by EPR have to be made so that any valuable resources and remove toxic substances (e.g., heavy metals) can be recovered during its treatment processes. Advanced recycling technologies of end-of-life LED lamps in South Korea are still needed for resource recovery. The EPR system for the lamps in the beginning of the year 2023 would help to accelerate their recycling, which is financially supported by the producers.

5. Conclusions

This study presents an overview of the current management practices of end-of-life fluorescent lamps, highlighting their mass flow and mercury flow using both the static and dynamic flow analysis methods. Limited previous studies reported the static mass flows of the lamps in the management systems [22,24,25]. Little is known about the dynamic mass flow of the lamps in the future, as they are being replaced with LED lamps. It is necessary to determine the quantitative flow of end-of-life fluorescent lamps for recycling and management in the coming years.

Recycling of fluorescent lamps has been commonly practiced to recover mercury for proper treatment and recyclable components (e.g., aluminum and glass) in many developed countries, while limited collection and recycling of the lamps from households has been practiced in many developing countries [27]. Mercury, a potential toxic metal, in fluorescent lamps should be properly treated from the view of pollution prevention. Otherwise, it may cause serious human health problems and environmental impacts upon improper disposal. Thus, environmentally sound management and resource recovery of fluorescent lamps is an pivotal issue of concern around the world. The used fluorescent lamps have been managed by EPR since 2004 in South Korea. Annual mandatory recycling rates for the lamps were usually achieved by the producers with concerted efforts on collection and recycling activities supported by households, local governments, and recycling facilities. In this study, static and dynamic MFA of fluorescent lamps and mercury in Korea was carried out and the following conclusions were drawn. The benefits of the MFA study for the lamps in resource and hazardous waste management as discussed in this study are as follows: first, the material balance of fluorescent lamps on a national level reveals the quantitative flows by life cycle and would help set the proper measures in resource and waste management. Second, the potential hazards and pathways of mercury in the lamps are identified in the collection and disposal stages; the toxic metal of mercury should be treated with care upon the lamp disposal. Third, without an investigation into the dynamic MFA, it is not likely that the substantial decrease in mercury lamps in the future can be quantitatively identified. Establishing the mass balance for fluorescent lamps and their mercury flow examined in this study would help waste policy decision-makers to identify resource recovery potentials and control toxic substances in the environment.

Based on the result of static MFA, approximately more than 33 million units of the used fluorescent lamps were generated in 2020, while 44.8 million units of new fluorescent lamps were placed on the market in the same year. Approximately 2957 tons (or 27.9 million units) of collected fluorescent lamps from households were processed by shredding and sorting methods by recovering mercury and recyclable parts in 2020. Only 328 tons (or 3.1 million units) and 223 tons (or 2.1 million units) of the lamps were disposed of incinerators and landfills, respectively. Mercury (278 kg) in the recycling process was recovered by carbon filters and subsequently treated at the hazardous incineration facilities in 2020. This recovery process is important because, often, the flow of mercury in the lamps can be uncontrolled, especially in developing countries, and cause accumulation and release of the toxic metal in the surrounding environment. In addition, because the collection and recycling rates of used fluorescent lamps can be changing constantly, it is necessary to analyze them periodically using MFA. This is especially true when many new LED lamps are being introduced into the market. Thus, routine and cost-effective determination of the waste flow over time is essential for sustainable resource waste management.

In 2021, mercury flow in the waste stream was determined to be approximately 394 kg in the generation of the used fluorescent lamps. In 2030, the expected amount of end-of-life fluorescent lamps to be retired was estimated to be approximately 14 million units, equivalent to 23 kg of mercury. This clearly indicates that mercury in the lamps considerably decreases with respect to time by the replacement of florescent lamps with LED lamps. The planned phase-out of fluorescent lamps by the Minamata Convention would result in lower demands by consumers. Thus, mercury flow in the lamps is also expected to continually decrease in the waste streams by 2030. Estimated mercury flow can change if there is a change in the basic data and assumptions used in the analysis of the dynamic material flow performed in this study. Therefore, uncertainty exists in the presented results, and future predictions should be complemented by verification and revision.

As LED lamps would be regulated by the EPR in the beginning of 2023 in South Korea, economically feasible and environmentally sound recycling technologies should be established by recovering rare earth elements and precious metals (e.g., indium, gallium, aluminum, silicon, cerium, yttrium, gold) as well as by removing toxic chemicals (e.g., arsenic, boron, copper, nickel) from the lamps towards sustainable resource management.

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