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ORIGINAL ARTICLE

Comprehensive analysis on mercury stream of cold cathode fluorescent lamps (CCFLs) in Korea (Republic of)

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Abstract

Due to the activation of the Minamata Convention, policies and treatment facilities for the safe management of mercury and mercury compounds have been developed in many countries, including Korea. In particular, cold cathode fluorescent lamps (CCFLs) should be managed safely because mercury was contained in CCFLs. However, the overall quantitative scale of CCFL as a kind of mercury-added product in Minamata Convention has not been evaluated in Korea. In this study, stream for LCD devices in Korea was analyzed from the stages of production through consumption to end-of-life using a market supply model. The mercury stream of CCFLs from LCD device was also estimated by characterization of CCFLs. As the backlight of the LCD device was converted to LED in the stage of production, there was no inflow of CCFLs into the stage of consumption from 2019. Considering the previously produced and distributed LCD devices with CCFLs in Korea, however, the stocked number in the stage of consumption in 2019 was estimated to be 227,727 thousand of CCFLs. In addition, the number of CCFLs and mercury amount in CCFLs at the stage of end-of-life were estimated to be 36,341 thousand and 65.90 kg, respectively.

Keywords Mercury content · Mercury stream · Cold Cathode Fluorescent Lamp · LCD device

Introduction

As the display technologies have developed, which used the advanced technologies with thinner, lighter and more flexible materials, the global market of the display has changed during the last three decades. However, the global market share of liquid crystal display (LCD) was still 75.1% and USD 93.1 billion in 2020 because the OLED display was very expensive [1]. Also, the flat panel display (FPD) equipment market has the potential to grow by USD 2.28 billion during 2021–2025 and the market's growth momentum will be increased at a CAGR of 4.05% [2]. LCD market share in China increased from 30.6% in 2018 to 44.2% in 2020 while that in Korea (Republic of) decreased from 29.2% in 2018 to 20.6% in 2020 [3]. The gap of LCD market share between China and Korea will be getting wider and wider.

LCD contained backlights such as Light Emitting Diode (LED) and Cold Cathode Fluorescent Lamps (CCFLs) to illuminate the screen. Under the Minamata Convention, IT panels using LCD with CCFLs should be controlled safely because mercury and mercury compounds are contained in CCFLs. Hence, it is crucial to estimate the amount of mercury and mercury compounds in CCFLs and to manage recycling facilities of LCD panels with CCFLs safely.

Chang et al. evaluated that 199 kg of mercury in CCFLs was in domestic sales through material flow analysis as of 2004 in Taiwan and explained the need for a policy for appropriate management of such mercury [4]. Zhuang et al. estimated that about 3400 million of CCFLs were stocked from 2003 to 2015 by the lifespan method in mainland China and found that the largest amount of mercury vapor was released into the environment when dismantling in the recycling of CCFLs [5]. Althaf et al. found that the change in technology from CRTs through LCDs with CCFLs to LCDs with LEDs in the United States resulted in a reduction of lead and mercury in spent display streams and a potential toxicity reduction in the electronic waste faction [6].

Since LCD devices with CCFLs are involved in the type of E-waste, the statistical distribution of lifespan can

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be applied to a market supply model as the methodology for estimating the amount of E-waste. Walk predicted the discarded CRT appliances in Baden-Württemberg, Germany, using a market supply model with the statistical distribution of lifespan. It was suggested that this method can be used to understand the effect of recycling options according to the time between production and end-of-life [7]. Kalmykova et al. evaluated the product flow and major substances for consumption and disposal using the market supply model with a lifespan on the technology transition from CRT to LCD [8]. They emphasized the importance of recycling capacity planning by technology transition of display devices.

In Korea, the mercury stream for mercury-added products listed in Part I of Annex A under the Minamata Convention was evaluated for target items in domestic production and imports. As a result, it was evaluated that 1.1 tons of mercury in mercury-added products were distributed in 2014 [9]. However, CCFLs from LCD panels were not included in the target items for the investigation of mercury stream even though waste LCD panels have been controlled by Eco-Assurance System (Eco-AS) since 2008 in Korea. In addition, the stocked amount at consumption and the generation amount at the stage of end-of-life of mercury-added products were not evaluated at all. Therefore, information on the mercury stream of CCFLs as mercury-added products was insufficient.

For Eco-AS in Korea, the produce responsibility organization (PRO) collects waste LCD panels and transports them to recycling centers, in which CCFLs are separated by manual and sent to special recycling companies of CCFLs [10, 11]. In the recycling processes of CCFLs, mercury must be separated from glass and phosphor powder, and the mercury content in CCFLs should be investigated. To control mercury in CCFLs, mercury flow analysis in recycling processes should be carried out. Oguchi et al. performed product flow analysis (PFA) in Japan for durable goods, including electronics such as desktop PCs and CRT displays by applying the concept of the lifespan model [12]. Additionally, it was explained that the results of PFA can be useful for performing substance flow analysis.

The focus of this study is to estimate the mercury amount and stream of CCFLs in Korea using the concept of a market supply model based on the statistical data of LCD devices flowing into the market. The characteristics such as the number, length, and others of CCFL included in LCD devices were analyzed. Also, CCFL from laptops, monitors for PC, and televisions were also analyzed to estimate the amount of mercury. The material flow analysis of LCD devices and mercury stream of CCFLs in Korea was carried out by describing the three stages such as production, consumption, and end-of-life to find the stocked number at consumption, the generation number at the end-of-life of LCD devices, and mercury amount of CCFLs.

Materials and methods

Analysis of characteristics of LCD device

There is a difference in the method of introducing light from the LCD device to the panel layer, including liquid crystal. According to the structure of the LCD device, it can be divided into edge type and direct type. Edge type is a method to install a light source located at one or both ends of light guide plate. Light is introduced into the panel direction by light guide plate and is intended to realize a thinner LCD device [13]. Direct type is a method in which a light source located behind the panel was entered directly into the panel [14].

The number of CCFLs in the LCD device varies with the type of display device, producers and production date. In the case of laptops and monitors for PC, the edge type was used in thinner products preferred by consumers applying 1–4 CCFLs as backlights [13, 15]. For television, the direct type of backlight was adopted to ensure high brightness over a large area [16]. Therefore, the direct type requires more light sources than the edge type, and at least 6 CCFLs are required [15, 17, 18].

For a comprehensive analysis of the mercury stream of CCFLs, CCFLs can be obtained from LCD devices such as laptops, monitors for PC, and televisions collected into a nationwide recycling center in Korea. The basic information on the number, length, diameter, weight, and lifespan of CCFLs in LCD devices was analyzed. The sample number of laptops and monitors for PC and television were 263 and 327, respectively.

Mercury analysis

Mercury amount in CCFLs was obtained using the comprehensive method carried out by Rhee [19]. It can be calculated by the sum of the mercury amount of vapor generated during lamp crushing and the mercury amount in components of CCFLs. An integrated approach is used for estimating the mercury amount of vapor from CCFLs which are crushed in a closed system [19, 20]. The mercury concentration of vapor generated during lamp crushing was analyzed using the Mercury Vapor Indicator (MVI, ION Science, USA). The mercury amount of vapor was evaluated by the concentration of mercury vapor, time and flow rate. To determine the mercury amount in components of CCFLs, mercury content was analyzed using the Direct Mercury Analyzer (DMA-80, Milestone, Italy). The mercury amount in components was estimated by multiplying the mercury content by the weight of the components. Also, the difference in mercury content of CCFLs from LCD, laptops and monitors for PC and television is due to manufacturer, production date and product size. Therefore, the mean and standard error were analyzed to indicate the reliability of the measured mercury content.

Evaluation method of mercury stream

The concept of material stream of LCD devices and mercury stream of CCFLs were evaluated by three stages such as production, consumption, and end-of-life as shown in Fig. 1. The stage of production is a section in which the LCD devices placed on the market can be grasped by domestic production and import/export amount. The stage of consumption is a stage in which the LCD devices are being used and stocked the amount of LCD devices. The stage of end-of-life is a section where the LCD device is generated as waste. In the stage of end-of-life, the treatment routes can be divided into recycling (official route) and other treatment (unofficial route). Recycling (official route) of LCD devices is directly related to the nationwide recycling center for E-wastes operated to achieve the goal of the domestic EPR system. However, the other treatment (unofficial route) is involved in the used market, junk shop, transboundary movement and others.

To estimate the amount of E-waste generation, the market supply model has been used under Commission Implementing Regulation (EU) 2017/699 in the European Union [21, 22]. The feature of the market supply model is to predict the amount of E-waste generation over time by applying the Weibull distribution, a continuous probability distribution, considering the lifespan. Therefore, in this study, the market supply model was used to estimate the mercury stream of CCFLs included in the LCD device, a type of e-waste.

The basic data required for the market supply model to estimate the mercury stream of CCFLs may be the statistical data of LCD devices flowing into the market and mercury content in CCFLs. Statistical data in Korea (Republic of) are shown

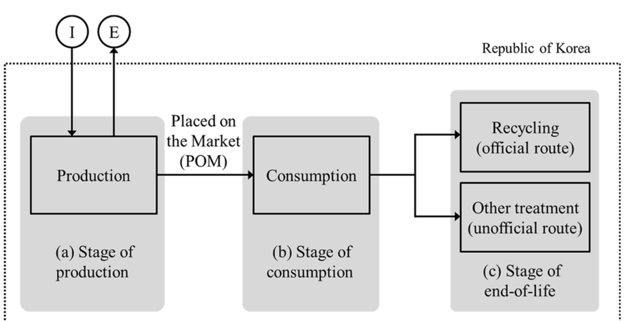


Fig. 1 Concept of material stream of LCD device and mercury stream of CCFLs in Korea

in terms of the total number of LCD devices without distinguishing backlights such as CCFLs and LEDs. Therefore, it is necessary to indicate that CCFLs are used in LCD devices. The amount of LCD devices with CCFLs was estimated by Eq. (1) using the placed on the market (POM) and the market share of backlight used in LCD devices.

$$\mathrm{POM}(t)_{\mathrm{CCFLs},t} = \mathrm{POM}(t)_{total,t} \times x_t \tag{1}$$

where $\mathrm{POM}(t)_{\mathrm{CCFLs},t}$ is the number of LCD devices with CCFLs, $\mathrm{POM}(t)_{total,t}$ is the total number of LCD devices that are imported and exported and the placed on the market (POM) at year t, and x_t is the market share of LCD devices with CCFLs at year t (For x_t, see supplementary material for a market share of LCD devices).

The number of LCD devices at the stage of end-of-life is estimated by the concept of the market supply model and can be described by Eq. (2) [12, 21, 22].

$$W(n) = \sum_{t=t_0}^{n} \mathrm{POM}(t)_{\mathrm{CCFLs},t} \bullet L^{(p)}(t,n) \tag{2}$$

where $W(n)$ is the total number of LCD devices with CCFLs in the stage of end-of-life for evaluation year n, $\mathrm{POM}(t)$ is the number of LCD devices with CCFLs placed on the market in any year t. t_0 is the original year when LCD device with CCFLs was placed on the market. The lifespan probability distribution $L(p)(t, n)$ means the conversion rate to waste in evaluation year n of LCD devices with CCFLs placed on the market in year t. It can be calculated by the Weibull distribution function applied with lifespan parameters such as the time-varying shape parameter $\alpha(t)$ and scale parameter $\beta(t)$ as shown in Eq. (3). [7, 21].

$$L^{(p)}(t,n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}}(n-t)^{\alpha(t)-1}e^{-\left[\frac{n-t}{\beta(t)}\right]^{\alpha(t)}} \tag{3}$$

When the lifespan parameters are not changed over time, the lifespan probability distribution can be simplified as Eq. (4) [21].

$$L^{(p)}(t,n) = \frac{\alpha}{\beta^{\alpha}}(n-t)^{\alpha-1}e^{-\left[\frac{n-t}{\beta}\right]^{\alpha}} \tag{4}$$

where α (alpha) is the 'shape parameter' of the probability distribution, β (beta) is the 'scale parameter' of the probability distribution.

The number of LCD devices with CCFLs stocked in the stage of consumption was calculated by subtracting the conversion rate to waste in the stage of end-of-life from the placed on the market as shown in Eq. (5) [22].

$$S(n) = \sum_{t=t_0}^{n} \mathrm{POM}(t)_{\mathrm{CCFLs},t}[1 - L^{(p)}(t,n)] \tag{5}$$

In this way, the estimated number of LCD devices with CCFLs at each stage can be obtained by the result of product-level material flow analysis. From the results, the level of mercury in mercury stream can be evaluated through the number and mercury content of CCFLs included in LCD devices by describing the method in "Analysis of characteristics of LCD device" and "Mercury analysis". Eventually, the number of CCFLs can be calculated by multiplying the number of LCD devices with CCFLs estimated in each stage by the average number of CCFLs in LCD devices. The number of CCFLs in each stage was converted to the amount of mercury using the average mercury content of CCFLs. Information on the lifespan of LCD devices with CCFLs brought into recycling facilities can be obtained by comparing the date of manufacture with the date of collection.

Results and discussion

Characteristics of LCD device with CCFLs

The specification for CCFLs in LCD devices was shown in Table 1. In the Table 1, the number of CCFLs is indicated by each (ea.), which means the unit of number of CCFLs. The number of CCFLs recovered from laptops and monitor for PC was between 1 and 4, showing a similar range in other studies [5, 18]. But Cryan et al. reported that the maximum number of CCFL values was 10 because it may be presumed to be a direct type [17]. The number of CCFL in LCD television ranged from 10 to 18 as the structure of direct type, which was similar to other studies [5, 17, 23, 24]. Televisions contained more CCFLs than laptops and monitors for PC because of requiring more light sources typically for the large area of televisions.

The average lifespan of laptops and monitors for PC was estimated to be 8.8 years and the 95% confidence interval range was 8.5–9.1 years. In the case of television, the average lifespan was estimated to be 11.21 years and the 95% confidence interval range was 10.1–11.5 years.

In several studies related to E-waste, the lifespan of LCD devices was estimated through a questionnaire survey of consumers and a comparison of the time of production marked on the product with the time of collection by recycling facilities. The average lifespan of laptops and monitors for PC and television was reported to be between 4 and 10.7 years [8, 12, 25, 26], and between 6 and 11.4 years [8, 12, 25, 26], respectively. Hence, the average lifespan estimated in this study was similar to that of laptops and monitors for PC and television shown in other studies.

The values of α and β can be decided from the slope and intercept of a linear line which can be obtained by converting the lifespan distribution function representing the probability density of Eq. (4) into a cumulative distribution function, then taking the natural logarithm. Weibull distribution of the LCD device based on the estimated lifespan was shown in Fig. 2. The lifespan of the investigated LCD devices was utilized to obtain α and β values for laptops and monitors for PC and television, as shown in Table 2.

Mercury content in CCFLs from LCD device

The mercury content in CCFLs from LCD devices was shown in Table 3. The range of mercury content in CCFLs was 0.23–1.06 mg/ea. for laptops and monitors of PC and 1.26–3.18 mg/ea. for televisions and it was similar to other studies [4, 18]. The mean value of mercury content for laptop and monitor for PC was analyzed to be 0.65 mg/ea and the standard error was 0.03 mg/ea. In the case of television, the mean value of mercury content was analyzed to be 2.22 mg/ea and the standard error was 0.05 mg/ea.

In addition, the range of CCFL length is 314–354 mm for laptops and monitors of PC and 700–959 mm for televisions,

Table 1 Specification of CCFLs in LCD device

Type	Length (mm)	Diameter (mm)	Weight (g)	No. of CCFLs in LCD device (ea.)	Remarks
Laptop and monitor for PC	315–354	2.4–2.8	0.8–1.3	1–4	This study
	320–390	2.0–2.5	1.5–3.0	2–4	McDonnel and Williams [18]
	250–515	–	–	1–4	Zhuang et al. [5]
	–	–	1.5	6	Buchert et al. [23]
	–	–	–	2–10	Cryan et al. [17]
Television	700–959	3.0–4.3	6.7–13.3	10–18	This study
	430–920	2.5–4.0	1.5–9.4	6–18	McDonnel and Williams [18]
	695–1040	–	–	10–24	Zhuang et al. [5]
	–	–	4.0	15	Buchert et al. [23]
	–	–	–	6–20	Cryan et al. [17]
	–	–	–	12–20	Elo and Sundin [24]

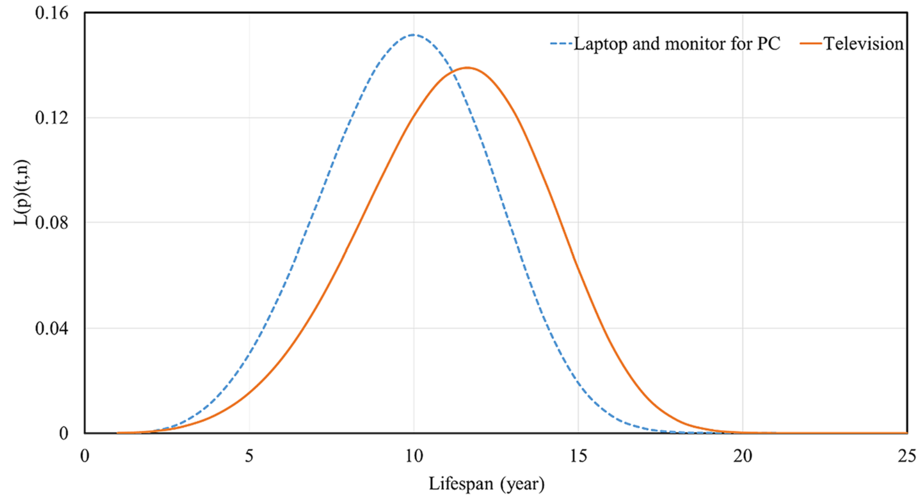


Fig. 2 Weibull distribution for LCD device with lifespan

Table 2 Weibull distribution parameters for LCD device with CCFLs

Type	Shape parameter (α)	Scale parameter (β)
Laptop and monitor for PC	2.88	8.22
Television	4.47	11.88

which corresponded to short and medium-length as classified under the Minamata Convention. CCFLs in LCD devices distributed in Korea (Republic of) must satisfy the mercury content limit according to the length of CCFLs under the Minamata Convention.

LCD device with CCFLs at the stage of production and consumption in Korea

In general, the concept of the place on the market (POM) using the market supply model is used by subtracting the export amount from the sum of production and import [8, 21]. National statistics on LCD devices in Korea are divided into import, export, shipment, and stock. The meaning of import and export is the amount of the exchange of goods between countries through international trade and the meaning of shipment is the amount that flows into the domestic market. Stock is the concept of the amount that does not flow into the market and stays at the stage of production. Since some statistics can't be provided to ensure confidentiality related to the business activities of companies [27], it is difficult to apply national statistics related to LCD devices in Korea to the concept of POM. To overcome the difficulty of statistics and obtain input data in the market supply model, it is necessary to carry out statistical management with long-term data related to LCD devices.

In addition, national statistics related to LCD devices are expressed as the total number of LCD devices regardless of the type of backlight used in the LCD devices. The number of LCD devices with CCFLs can be obtained using Eq. (1) with the total number of LCD devices. In Eq. (1), x_t is represented to be the market share of LCD devices using CCFLs as backlights. Figure 3 shows the market share of LCD devices using CCFLs and LED as backlights in households and offices. In the initial stage of the market release of LCD devices, 100% of LCD devices used CCFLs as backlights as shown in Fig. 3. LEDs started being introduced as backlights in 2009 and have dominated the backlight market since the middle of the 2010s. However, some displays in medical devices for special purposes, such as UV lamps for psoriasis still used CCFLs.

Statistics on imports and exports were extracted from Korea's trade statistics system [32], and converted to LCD devices with CCFLs by Eq. (1) as shown in Fig. 4a. At the beginning of the introduction of LCD devices, imports were larger than exports, but exports were greater than imports in 2007. The Korean display industry has increased LCD device production as a main item after introducing an LCD device. Since 2012, imports have increased due to the decrease in LCD production and the development of next-generation displays such as LED and OLED [3, 33].

Table 3 Mercury content in CCFLs from LCD device (unit: mg/ea.)

Source of CCFLs	This study (mean)	Chang et al. [4]	McDonnel and Williams [18]
Laptop and monitor for PC	0.23–1.06 (0.65)	0.5–2.5	Up to 3.88
Television	1.26–3.18 (2.22)		

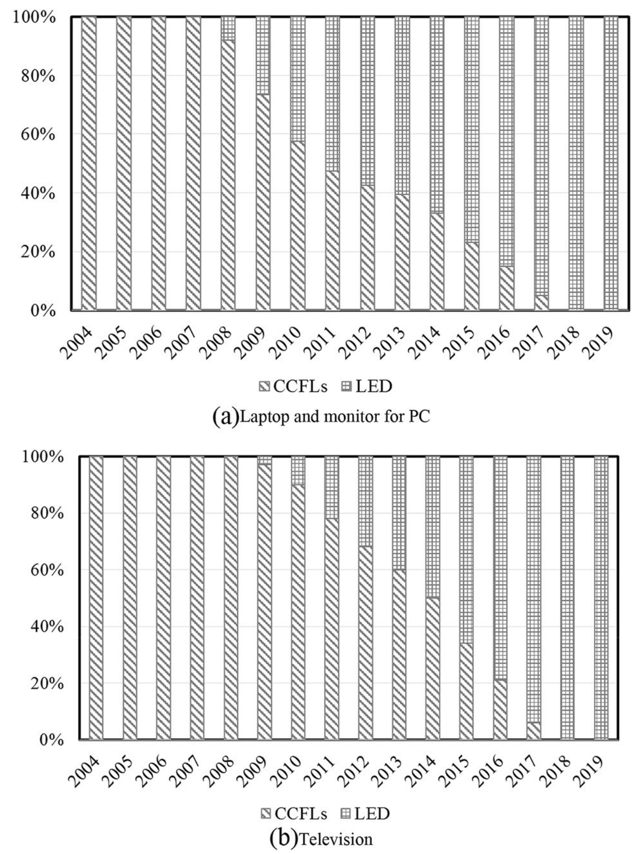


Fig. 3 Market share of CCFLs and LED backlight in LCD device [28–31]. **a** Laptop and monitor for PC. **b** Television

The dotted line in Fig. 4b indicates the total LCD device, including both CCFLs and LED backlights [34]. Until 2011, the total LCD devices showed a clear increasing trend and a constant and similar market inflow up to 2019. The bar chart in Fig. 3b shows the POM trend of LCD devices with CCFLs calculated by Eq. (1). LCD devices with CCFLs were released on the market and showed the highest value of POM in 2009, but LCD devices with CCFLs started to decrease from 2010. Since the consumption of LEDs as backlights for LCD devices has gradually expanded over time, the POM of LCD devices with CCFLs continuously decreased until 2017 and then disappeared in 2018.

LCD device with CCFLs at the stage of end-of-life in Korea

Figure 5 shows the estimated number of LCD devices with CCFLs at the stage of end-of-life from 2004 to 2037. The cumulative number of LCD devices with CCFLs at the stage of end-of-life, which had been introduced to the Korean market, was estimated to be 40,016 thousand in 2037. The annual $W(n)$ was estimated to be the largest in 2019 and the number of LCD devices with CCFLs in 2019 was 3503 thousand.

In the case of laptops and monitors for PC, it is predicted that the number of them with CCFLs of 18,508 thousand will be cumulatively generated in 2035. Also, the annual number of them with CCFLs peaked in 2019 and laptops and monitors for PC of 1706 thousand in 2019 were transferred to the stage of end-of-life. In the case of television at the stage of end-of-life, the number of televisions peaked at 1829 thousand in 2020 and the cumulative number of television was estimated to be 21,508 thousand in 2037.

The average weight of E-waste brought into the nationwide recycling center between 2009 and 2019 in Korea was investigated to be 3.6 kg for laptops and monitors for PC and 26.7 kg for televisions by Korea Electronics Recycling Cooperative (KERC) as a producer responsibility organization (PRO) [35]. Using this average weight and $W(n)$, the weight of LCD devices with CCFLs at the stage of end-of-life in 2019 was estimated to be about 54 thousand tons.

The total amount placed on the market and the total recycled amount of Electrical and Electronic Equipment (EEE), which are obligated to collect and recycled under the Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles in Korea, were about 990 thousand tons and about 322 thousand tons, respectively [36]. The amount of LCD devices with CCFLs estimated in 2018 was 5% of the total amount placed on the market of EEE and 16% of the total recycled amount of E-waste in Korea.

Mercury stream of CCFLs in Korea

CCFLs stream from LCD devices and mercury stream of CCFLs in Korea are shown in Fig. 6 by three stages of production, consumption, and end-of-life. Figure 6a shows the CCFLs stream from LCD devices to estimate the number of CCFLs at end-of-life. At the stage of production in 2015, the number of CCFLs of 12,940 thousand was imported and that of 13,059 thousand were exported. The POM between production and consumption was 19,234 thousand of CCFLs in 2015. However, there was no import, export and POM for LCD devices with CCFLs in 2019 because the backlight of LCD devices had been replaced with LEDs from CCFLs. In addition, as explained in "LCD device with CCFLs at the stage of production and consumption in Korea", the stock amount is unknown at the stage of production due to undisclosed information in Korea. At the stage of consumption, it can be indicated the number of stock uses CCFLs in the LCD devices through the CCFLs stream from consumption to end-of-life. The stocked number of CCFLs at the stage of consumption decreased from 343,627 thousand in 2015 to 227,727 thousand in 2019. The number of CCFLs transferred to the stage of end-of-life was increased from 21,780 thousand in 2015 to 36,341 thousand in 2019.

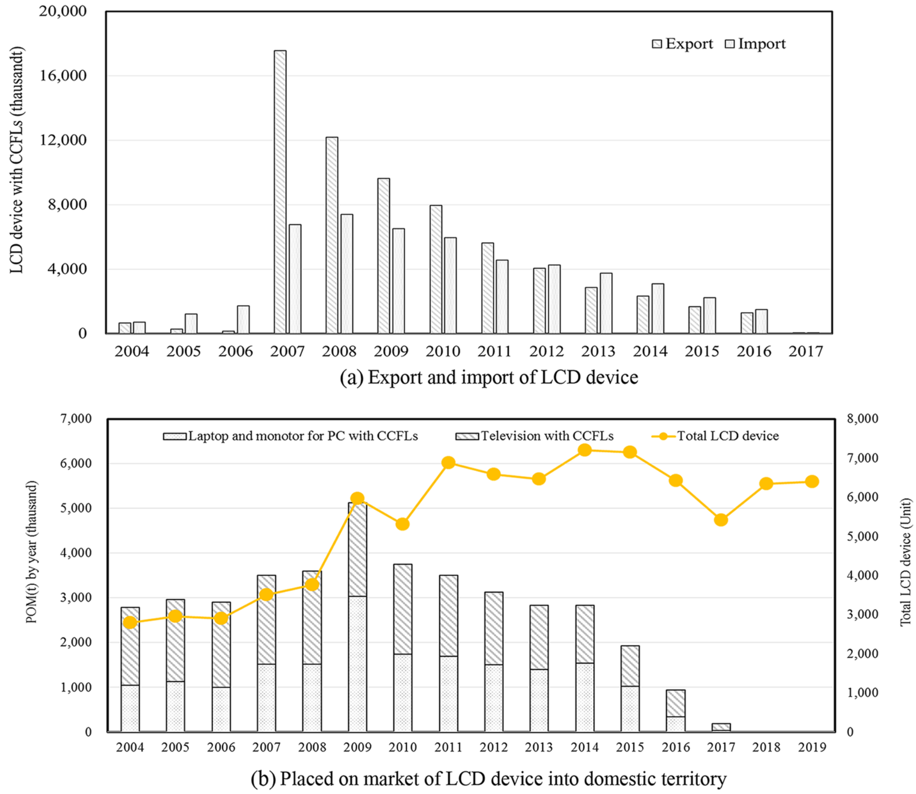


Fig. 4 Production and consumption of LCD device in Korea (Republic of). **a** Export and import of LCD device. **b** Placed on market of LCD device into domestic territory

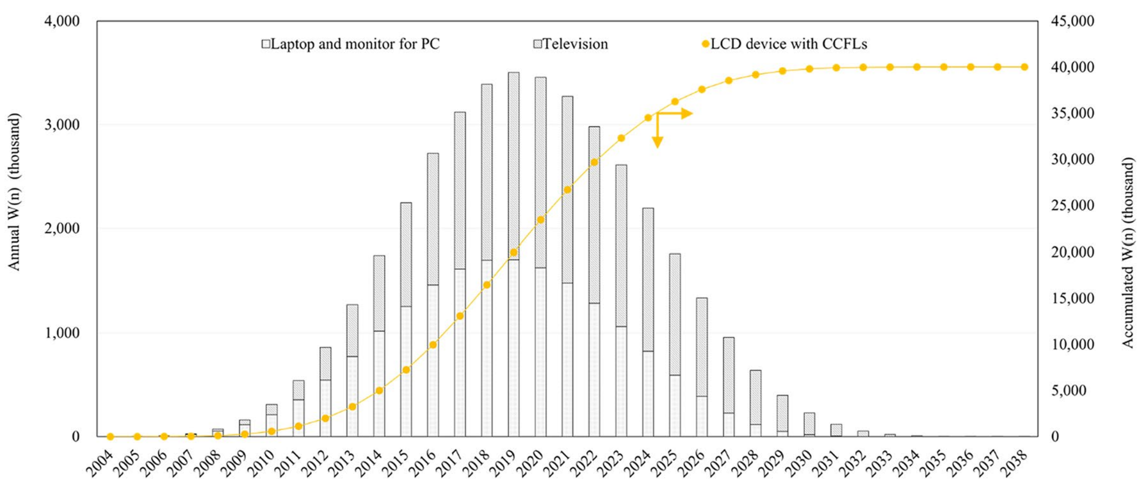
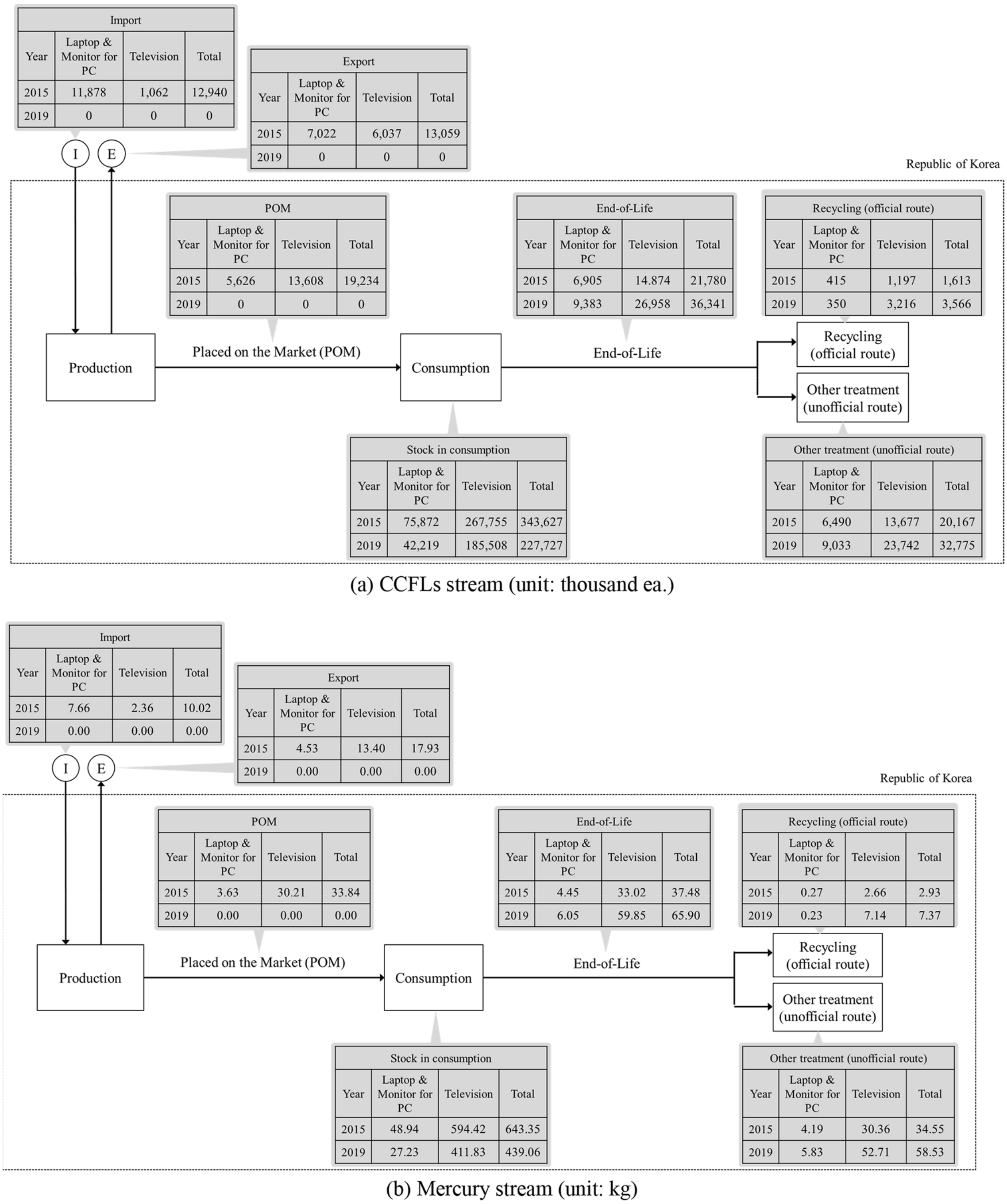


Fig. 5 Estimated amount of LCD device with CCFLs at the stage of end-of-life

At the stage of end-of-life, the number of CCFLs transferred to recycling (official route) means the amount brought into recycling companies licensed in Korea. A total of 181 thousand LCD devices with CCFLs were brought into recycling companies in 2014 with a compound annual growth rate of 18% from 2014 for five years [36, 37]. Therefore, the number of CCFLs for recycling (official route) in 2015 was 1613 thousand, which was about 7% of total CCFLs at the stage of end-of-life. And it was estimated that about 93% of CCFLs were transferred to other treatment (unofficial route). In 2019, the number of CCFLs in recycling (official route) was 3,566 thousand (about 10% of the total CCFLs at the stage of end-of-life).

The mercury stream of CCFLs is shown in Fig. 6b to estimate the mercury amount from CCFLs at each stage. The mercury amount from CCFLs in each stage shows a similar trend to the number of CCFLs in CCFLs stream. With respect to the trend of imports and exports of LCD



(a) CCFLs stream (unit: thousand ea.)

Import			
Year	Laptop & Monitor for PC	Television	Total
2015	11,878	1,062	12,940
2019	0	0	0

Export			
Year	Laptop & Monitor for PC	Television	Total
2015	7,022	6,037	13,059
2019	0	0	0

POM			
Year	Laptop & Monitor for PC	Television	Total
2015	5,626	13,608	19,234
2019	0	0	0

End-of-Life			
Year	Laptop & Monitor for PC	Television	Total
2015	6,905	14.874	21,780
2019	9,383	26,958	36,341

Recycling (official route)			
Year	Laptop & Monitor for PC	Television	Total
2015	415	1,197	1,613
2019	350	3,216	3,566

Stock in consumption			
Year	Laptop & Monitor for PC	Television	Total
2015	75,872	267,755	343,627
2019	42,219	185,508	227,727

Other treatment (unofficial route)			
Year	Laptop & Monitor for PC	Television	Total
2015	6,490	13,677	20,167
2019	9,033	23,742	32,775

(b) Mercury stream (unit: kg)

Import			
Year	Laptop & Monitor for PC	Television	Total
2015	7.66	2.36	10.02
2019	0.00	0.00	0.00

Export			
Year	Laptop & Monitor for PC	Television	Total
2015	4.53	13.40	17.93
2019	0.00	0.00	0.00

POM			
Year	Laptop & Monitor for PC	Television	Total
2015	3.63	30.21	33.84
2019	0.00	0.00	0.00

End-of-Life			
Year	Laptop & Monitor for PC	Television	Total
2015	4.45	33.02	37.48
2019	6.05	59.85	65.90

Recycling (official route)			
Year	Laptop & Monitor for PC	Television	Total
2015	0.27	2.66	2.93
2019	0.23	7.14	7.37

Stock in consumption			
Year	Laptop & Monitor for PC	Television	Total
2015	48.94	594.42	643.35
2019	27.23	411.83	439.06

Other treatment (unofficial route)			
Year	Laptop & Monitor for PC	Television	Total
2015	4.19	30.36	34.55
2019	5.83	52.71	58.53

Fig. 6 CCFLs and mercury stream in Korea (Republic of). **a** CCFLs stream (unit: thousand ea.). **b** Mercury stream (unit: kg)

devices with CCFLs, there was no mercury stream in 2019. In the POM, mercury amount was estimated to be 33.84 kg in 2015, but it was evaluated that there was no mercury inflow in 2019 due to the continuous decrease of the number of CCFLs over time. At the stage of consumption, the stocked mercury amount decreased from 643.35 kg in 2015 to 439.06 kg in 2019 because the POM of CCFLs decreased and the number of CCFLs at the stage of end-of-life increased.

At the stage of end-of-life in 2019, the mercury amount was estimated to be 65.90 kg, with almost a double increase compared to 2015. At the stage of end-of-life, the mercury amount in CCFLs entering recycling (official route) was increased from 2.93 kg in 2015 to 7.37 kg in 2019. However, the amount of mercury in recycling (official route) was lower than that in other treatment (unofficial route).

In "LCD device with CCFLs at the stage of end-of-life in Korea", the final year for LCD devices with CCFLs to move to the stage of end-of-life was estimated to be 2037. Nevertheless, the final year for LCD devices with CCFLs at the stage of end-of-life was likely to be extended because of CCFLs in other treatments (unofficial route). This is a limitation in that there is almost no information on other treatments (unofficial route) at the stage of the end-of-life. However, providing comprehensive information on CCFLs and mercury streams can be useful in the design of policy and recycling capacity for CCFLs. Furthermore, sustainable management measures for mercury in CCFLs should be implemented to convert from the other treatment (unofficial route) to the recycling (official route).

Conclusion

As a basis on the implementation of the Minamata Convention, the mercury stream in Korea was investigated, but mercury contained in LCD devices with CCFLs was not reflected in the mercury stream. To evaluate the mercury stream of CCFLs in Korea, the characterization of CCFLs in the LCD devices and the analysis of the mercury content of CCFLs were carried out. By applying the market supply model, the mercury stream of CCFLs was quantitatively evaluated through 3 stages of production, consumption and end-of-life. The major conclusions are as follows:

1. The range of mercury content of CCFLs in the LCD devices was estimated to be 0.23–1.06 mg/ea. for laptop and monitor for PC and 1.26–3.18 mg/ea. for televisions.
2. Mercury from the stage of production to the stage of consumption in the CCFLs stream was absent in 2019 because LCD device backlights were replaced with LEDs.
3. The stocked number of CCFLs in the stage of consumption decreased from 343,627 thousand in 2015 to 227,727 thousand in 2019. As the stocked amount of CCFLs decreased, the stocked mercury amount decreased from 643.35 kg in 2015 to 439.06 kg in 2019. Furthermore, it is predicted that LCD devices with CCFLs will be generated as wastes by 2037, so mercury in CCFLs will continuously generate as wastes until 2037.
4. At the stage of end-of-life in 2019, the amount of CCFLs and mercury was estimated to be 36,341 thousand ea. and 65.90 kg, respectively. In particular, the amount of CCFLs and mercury treated in the recycling (official route) was estimated about 10% of the total amount of CCFLs estimated at the stage of end-of-life.
5. The results of this study can be referred to estimate the capacity of an appropriate treatment facility to safely manage mercury in CCFLs through 3 stages of production, consumption, and end-of-life. Furthermore, sustainable management measures for mercury in CCFLs should be implemented to flow into the recycling (official route) from the other treatment (unofficial route).

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