Journal of Cleaner Production 133 (2016) 451–458

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Mercury flow analysis and reduction pathways for fluorescent lamps in mainland China

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ARTICLE INFO

Article history:
Received 21 August 2015
Received in revised form
15 May 2016
Accepted 16 May 2016
Available online 25 May 2016

Keywords:
Mercury flow
Fluorescent lamps
Mercury reduction
Material flow analysis (MFA)

ABSTRACT

China is one of the largest consumers and producers of fluorescent lamps in the world, and mercury from a large number of spent fluorescent lamps can enter the solid waste stream every year. However, detailed information about the quantity and the fate of mercury caused by fluorescent lamps is unavailable. This study quantified and determined the fate and flow of mercury in fluorescent lamps from manufacture to disposal using the material flow analysis (MFA) method. Indirect mercury emissions, which were from coal consumption during the use phase, were calculated. The pathways for mercury reduction were also discussed. It was estimated that the mercury contained in fluorescent lamps for domestic production, export and import in 2011 was 29.31, 12.81 and 3.95 tons, respectively. The mercury in the domestic usage category was 20.45 tons, of which 3.89 tons was sent for incineration and 15.54 tons was sent to landfill at the end-of-life phase, but only 0.97 tons of mercury was recovered. During the use phase, 27.51 tons of mercury was released to the atmosphere, and 11.79 tons was released to the land. The total amount of mercury emissions to the atmosphere and land was 28.31 and 30.47 tons, respectively. Manufacturing low-mercury-content lamps, reducing coal consumption during the generation of electricity and increasing the recycling rate of lamps can all significantly reduce mercury emissions to the environment.

1. Introduction

Mercury is a significant public health and environmental concern because of its toxic, persistent, and bioaccumulative properties (Tchounwou et al., 2003). Mercury is present in nature and has been released into the environment for centuries resulting from anthropogenic activities. As one of the most toxic elements in the periodic table, mercury and its compounds have adverse effects on the nervous system and its development, as well as adverse effects on the cardiovascular system, immune system, reproductive system and kidneys, especially for infants, children and pregnant women (Söderholm, 2013; UNEP, 2013a). Furthermore, mercury can circulate in the atmosphere, oceans, and terrestrial system for centuries to millennia before it returns to deep-ocean sediments (Selin, 2009). In addition, global warming and climatic changes can accelerate mercury remobilization and bioaccumulation in the environment and ecosystem with an increasing risk of human exposure (Raposo and Roeser, 2001). Consequently, it is increasingly important to reduce the emissions of mercury from human activities.

The United Nations Environment Programme (UNEP) has determined that mercury compounds are global pollutants and have made efforts to control them (UNEP, 2008, 2013b). In 2013, the Minamata convention was adopted by delegates from over 140 countries (UNEP, 2013c). It is becoming more crucial to determine sources of mercury to offer a reference for the control of mercury pollution. Fluorescent lamps (FLs) are a significant mercury-containing product and they are increasingly being used for general lighting. FLs contain mercury for generating ultraviolet radiation, which then is converted into visible light by ultraviolet light (UV) excitation of a fluorescent phosphors coating on the glass envelope of the lamp (European Commission, 2013). FLs' energy

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http://dx.doi.org/10.1016/j.jclepro.2016.05.101
0959-6526/

efficiency is higher than incandescent lamps, as a result many countries are phasing out incandescent lamps, including China (NDRC, 2011), the U.S., the European Union, Australia and Canada (Ramroth, 2008; Waide, 2009). Although the amount of mercury contained in each lamp is relatively small, usually several milligrams (Li and Jin, 2011; Rey-Raap and Gallardo, 2012; Sarigiannis et al., 2012), the large market for lighting means significant mercury consumption.

In addition, China is one of the largest FL consuming and producing countries in the world. In 2011, domestic production of compact fluorescent lamps in China accounted for over 80% of the world's production (MIIT et al., 2013). FLs are expected to dominate the lighting market in China, however, detailed information about the quantity and the fate of mercury caused by fluorescent lamps has not yet been produced. Mercury from FLs can be released into the environment and pose a threat to humans and ecosystems, particularly in the end-of-life stage. As China is a developing country, the mercury pollution caused by spent FLs can be very serious, therefore an investigation into the mercury flow of FLs in China is highly important.

Material flow analysis (MFA), as a systematic assessment of the flows and stocks of materials with a system defined in space and time, enables the identification and quantification of sources of a substance into a study system (Brunner and Rechberger, 2004). This can help decision makers to understand the metabolism of a specific society or region and has already been used to analyze the mercury flow in some countries, such as Europe (Sundseth et al., 2012), the United States (Cain et al., 2007), Denmark (Christensen et al., 2004), India (Burger Chakraborty et al., 2013), Japan (Asari et al., 2008) and Poland (Panasiuk and Głodek, 2013). These studies discuss mercury flow for all mercury-containing products, yet the role of FLs is small and vague. Christensen et al. (2004) analyzed the consumption and disposal of mercury and its release to the environment in Denmark in 2001. The consumption of mercury by light sources was 0.06–0.17 tons compared with the total consumption of 2.1–5 tons each year. In addition, the production, import, export, and waste management of FLs has not been studied. Another important aspect is the severity of mercury pollution caused by FLs. Cain et al. (2007) used substance flow analysis to develop improved estimates of the environmental releases caused by mercury-containing products in the United States. For FLs in 2005, the total input of mercury was 7.686 tons, but total release was 7.177 tons. Asari et al. (2008) studied the Japanese mercury flow of mercury-containing products from manufacture to disposal. The quantity of mercury from all products was about 10–20 tons annually, 5 tons of which was from FLs. Most FLs were disposed of as waste, and only 0.6 tons of mercury was recovered annually. The management of spent FLs and the pathways for mercury reduction are not covered by these studies. Compared with developed countries, mercury pollution caused by FLs in China may be worse due to the lack of efficient recycling systems and infrastructure (e.g. mercury capture and stabilization system) for the spent FLs. However, few studies have been made to estimate mercury emissions in China.

This study quantifies and determines the fate and flow of mercury in FLs from their manufacture to their disposal using the material flow analysis (MFA) method. Indirect mercury emissions, which are from coal consumption during the use phase, are calculated. The pathways for mercury reduction are also discussed. The results could offer a reference for the control, management, and treatment of FLs and provide policy makers with a better understanding for reducing the release of mercury from FLs.

2. Methodology

MFA is based on the principle of the conservation of matter, and it connects the sources, the pathways, and the intermediate and final sinks of a material (Brunner and Rechberger, 2004). And it includes four major steps, namely goal and system definition, data acquisition and inventory, material balances and modeling, and interpretation (Hendriks et al., 2000). The mercury flow of FLs is generally confined to three phases: production phase, use phase and disposal phase of end-of-life FLs. The system boundaries exclude the raw material extraction and transportation etc. because mercury emissions in these stages are relatively small and public data is unavailable. The time margin is the year 2011, and the basic data is complemented by literature study. The mercury emissions include direct emissions and indirect emissions. Indirect mercury emissions are from coal consumption during the use phase. The model of mercury flow is illustrated in Fig. 1.

2.1. Production

There are several different kinds of fluorescent lamps, including compact fluorescent lamps (CFLs), linear fluorescent lamps (LFLs) and circular fluorescent lamps (CirFLs). The amount of mercury contained in FLs in production, import, export or domestic use is formulated as Eq. (1).

$$M_i = Q_{CFL} \cdot C_{CFL} + Q_{LFL} \cdot C_{LFL} + Q_{CirFL} \cdot C_{CirFL} \quad (1)$$

Where M_i is the mercury contained in FLs of the production, import, export or domestic use. Q_{CFL}, Q_{LFL} and Q_{CirFL} are the quantities of CFLs, LFLs or CirFLs, respectively. C_{CFL}, C_{LFL} and C_{CirFL} are the average mercury content per CFL, LFL or CirFL, respectively. According to the industry standard, the mercury content of each CFL should be less than 5 mg, and less than 10 mg for each LFL (NDRC, 2008). Various FLs contain different amounts of mercury, it is documented that mercury amounts typically vary from 1.7 mg to 15 mg per lamp (U.S. EPA, 2009). If mercury content of each CFL and LFL is assumed to be 5 mg and 10 mg, the calculated results can be higher than the actual results. Thus, we consider the average mercury content of each CFL as 2.5 mg, and for the LFL and CirFL as 7.5 mg.

$$M_{production} + M_{import} + S_{2010} = M_{use} + M_{export} + S_{2011} \quad (2)$$

Where $M_{production}$, M_{import}, M_{export}, M_{use} is the mercury contained in FLs of the production, import, export and domestic use, respectively. S_{2010}, S_{2011} is the stock in the year 2010 and 2011, respectively, which means that lamps are produced but not sold to the customers.

As very few FLs are stocked according to the statistical data, the items S_{2010} and S_{2011} in Eq. (2) are ignored, and Eq. (2) can be simplified as Eq. (3).

$$M_{production} + M_{import} = M_{use} + M_{export} \quad (3)$$

Data regarding quantities of mercury in domestic production is obtained from the National Bureau of Statistics (NBS, 2012). Quantities of FLs in production, import, export and domestic use in China are obtained from Tan and Li (2014).

2.2. The use phase

For the use phase, it should be noted that mercury emissions are not the direct emissions from FLs and are modeled on the basis of energy consumption in the generation of electricity. In order to ascertain the amount of mercury emissions from the electricity