Assessment of Mercury Flows through Fluorescent Lamps and Potential Reduction Scenarios in Thailand

Manaporn Wongsoonthornchai, Suphaphat Kwonpongsagoon, and Ruth Scheidegger

***Abstract*—Fluorescent lamps (FLs) have been widely used in Thailand due to the energy saving policy in the past. This has led to a large amount of mercury (Hg) flows and stock in Thailand. Mathematical Material Flow Analysis (MMFA) was applied to estimate the Hg flows and stock through FLs in Thailand, based on data in the year of 2010. The results showed that around 526 kg of Hg was imported for FL production and 43 kg of Hg was imported with FLs, whereas 7 kg was exported with FLs. Hg was stocked in use around 1,100 kg. The results also showed that about 474 kg of Hg in FL waste was sent to dispose of or to recycle. Hg was released in the environment from FL production, use and the disposal stage at around 562 kg, with 84% going to land, 12% to air, and 4% to water. The scenario analysis in this study showed that limiting the Hg content of FLs to 2.5 mg per lamp has a high potential for reduction of Hg emissions, and that the replacement all FLs with light-emitting diode (LED) is a feasible strategy to reach Hg zero emission.**

***Index Terms*—Emission, fluorescent lamps (FLs), material flow analysis (MFA), mercury.**

I. Introduction

Mercury (Hg) has been used in several products because of its properties, the fluorescent lamp (FL) is one of them. In the fluorescent bulb, Hg is used to convert electrical energy to radiant energy in the ultraviolet range, which is then re-radiated in the visible spectrum by the "phosphor" compounds that coat the inside of the bulb [1]. In Thailand, the use of FLs was initially promoted around the year of 1996 by a campaign to replace incandescent lamps with compact FLs to save energy [2]. Ten years after this campaign, the government decided on a policy to ban all incandescent lamps in Thailand [2]. This increased the market share for FLs to around 30% while the market share of incandescent lamps gradually decreased to around 30-40% [3]. In 2012, the Pollution Control Department (PCD) reported that the use of FLs in Thailand increased from 101 million lamps in 2007 to 123 million lamps in 2010 [4]. Along with the increased use of FLs, the FL waste stream of the country has surged. The preliminary report of the Pollution Control Department showed that about 41 million spent fluorescent lamps were generated from Thailand in 2004 [5]. It can be inferred that a high rate of FL waste has been generated in Thailand since 2000.

Hg is released into the environment if the FLs are broken, incinerated, or disposed of at landfills [6]. The effects of carcinogens and ecotoxicity from the use and treatment of FLs have been reported in other studies [7], [8]. Elemental Hg released from FLs can cause a concern because it can be converted to methylmercury the most toxic form of Hg and the most commonly found in the environment [1]. Methylmercury (CH_3Hg) is classified as having "possible carcinogenic effects to humans" (group 2B) by the International Agency for Research on Cancer (IARC) [9] and Hg is prioritized as one of the hazardous air pollutants (HAPs) related to the Clean Air Act of the US.EPA [10]. Hg not only affects human health, but also animals in the same environment. It can accumulate in organisms, harm bird reproduction and behavior, and endanger aquatic animals, e.g., fish and predatory organisms, and affects some ecosystems [11]. Because of the adverse effects for both environment and human health, Hg has been identified as a serious global problem.

To respond to the concern of Hg pollution, the United Nations Environment Programme (UNEP) established the "Minamata Convention on Mercury" in 2010 to protect human health from any Hg toxicity. This global convention enforces its members to phase out FLs by 2020 if Hg content exceeds 5 mg per lamp [12]. The Minamata Convention has not yet been signed by Thailand.

As mentioned above, Thailand has achieved energy saving through a campaign for using FLs instead of incandescent lamps, however the problem of FL waste management and its residual Hg management has been overlooked. This remains a big environmental issue in Thailand. Appropriate measures to reduce Hg pollution from FLs in Thailand have to be considered, although the Hg content in FLs produced in Thailand does not exceed 5 mg per lamp.

To understand the Hg flows through FLs in Thailand, Mathematical Material Flow Analysis (MMFA) was used in this study to describe, and interpret the flow and stock of Hg in FLs. The results will then be used to assess to and propose potential reduction scenarios for Hg pollution from FLs in Thailand.

II. Method

The method of MMFA, extended from traditional Material Flow Analysis (MFA) with modeling concepts, was developed by Baccini and Bader [13]. The MMFA steps are described below.

1) *System analysis*: is defined as both temporal and spatial

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boundaries of the system, and defined by the processes related to FLs;

2) *Mathematical model*: involves the formulated mathematical equations to describe fluorescent flows and stock in Thailand;
3) *Data acquisition and calibration*: means the collected and calibrated data for the model;
4) *Simulation and uncertainty analysis*: comprises simulated current situation including uncertainty;
5) *Sensitivity and scenario analysis*: identifies the key parameters associated with the main flows and simulates the measures to reduce Hg emission from FLs.

The method of MMFA was described in details by Bader and Scheidegger [14] and Kwongpongsagoon *et al*. [15], [16].

A. System Analysis

Fig.1 shows the system analysis of the Hg flows through FLs in Thailand in 2010. Hg is imported for FL manufacturing, and in FLs. Hg containing FLs are domestically produced, most of them are used domestically and the rest is exported, causing Hg flows through FLs in the production, use, and disposal phases. During the use phase as well as the production and disposal phases Hg is emitted to the environment. The disposal phase includes the box of “Solid waste”, hazardous waste treatment “HWT”, and “Recycle”. In this study, the sources of FL waste are separated in two types: 1) household (HH), and 2) industrial, commercial and services (ICS) e.g., industry, hospital, department store, office building.

The system of equations was solved by the SIMBOX simulation program explained below.

B. Mathematical Model

The model approach was stationary. The method of MMFA was based on mass balance principle and specific equations. The mass balance is:

$$Mar(i) = \sum(input) - \sum(output) \quad (1)$$

where:

$\sum$ = The sum includes all inputs and outputs to and from the process *i*

$Mar(i)$ = The mass or substance changed with respect to time

Input equations:

$$I_{FL} = FL_{Import} \times C_{FL\_imp}$$
$$I_{Hg} = FL_{Dom\_prod} \cdot C_{FL\_dom} + E_{Air\_prod} \quad (2)$$

where:

I_{FL} = Import of Hg in FLs

I_{Hg} = Import of Hg for domestic production

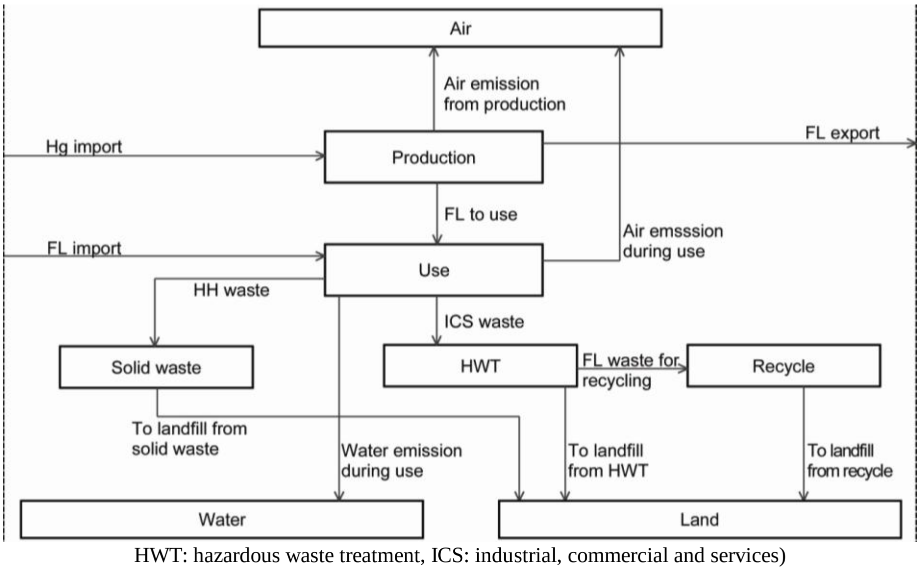
FL_{Import} = Number FLs imported

FL_{Dom_prod} = Number of FLs produced domestically

C_{FL_imp} = Content of Hg in FLs imported

C_{FL_dom} = Content of Hg in FLs produced domestically

E_{Air_prod} = Emission to air from Production



HWT: hazardous waste treatment, ICS: industrial, commercial and services)
Fig. 1. System analysis for Hg flow through FLs in Thailand, 2010 (FL: fluorescent lamp, HH: household.

Output equations:

$$O_x(i) = I_{tot}(i) \cdot k_x(i) \quad (3)$$

where:

$O_x(i)$ = Estimated Hg in pathway *x*

$I_{tot}(i)$ = Total Hg input with Hg containing products into process *i*

$k_x(i)$ = Distribution factor of process *i* to pathway *x*

The flows and environmental releases of Hg can be calculated using (1) to (3). The results will be expressed in kilograms of Hg per year [17].

C. Data Acquisition and Calibration

The input data for 2010 in this study was separated in 1) primary data and 2) secondary data. Primary data of the concentration of Hg in domestic FLs was collected from relevant companies in Thailand. Secondary data, including number of imports, exports, and production of FLs, Hg concentration of imported FLs, emission factors, waste generation per household, number of households, and average lifetime of lamps, was obtained from literature review [4], [18]-[22].

III. Results and Discussion

A. Hg Flows and Stock through FLs in Thailand

Fig. 2 shows the estimation of Hg flows through FLs in Thailand within the year of 2010. Thailand imported, produced, and exported FLs in 2010, about 9.5, 115, and 1.5 million lamps, respectively [4]. The Hg contained in imported and domestically produced lamps is around 4.5 mg/lamp [19], [20], [22]. It was estimated that 569 kg of Hg were imported, with 92% imported for domestic FL production and the rest found in imported FLs. Thailand exported Hg in FL around 7 kg/year. Hg can be emitted to the environment from FL breakage during use [18]. The simulation showed that the FL production emitted about 10 kg Hg to the air while around 55 kg Hg was released to air and around 22 kg was released to water during use. We assumed a lifetime of two years for FL [23], which resulted in a stock of around 1,100 kg Hg in FL in use. 52% of FL waste was generated from industries, commercial and services (ICS) and collected in HWT, the rest (48%) was generated from households (HHs). Since Thailand has no system of municipal solid waste and hazardous waste separation at source, all spent FLs from HHs (around 229 kg Hg) collected by local municipal administrator was disposed on landfills. About 245 kg of Hg in FL wastes from ICS went to hazardous waste treatment. Most were disposed of by landfilling. Only about 18% went to recycling plants (see Fig. 2), resulting in a current recycling rate of FL wastes in Thailand of about 9% of total FL wastes. According to the Pollution Control Department (PCD), the pilot project for collection of spent FLs from ICS waste was first attempted in 2006. Only large-scale waste generators, namely industries, hospitals, department stores, and office buildings have been involved in this project [23]. However, in Thailand the technology for recycling FL waste is limited. Only glass and end caps were separated and recycled whereas Hg was discarded in secure landfills with a stabilization/solidification process [24]. This meant that no Hg was recycled from FL wastes in Thailand.

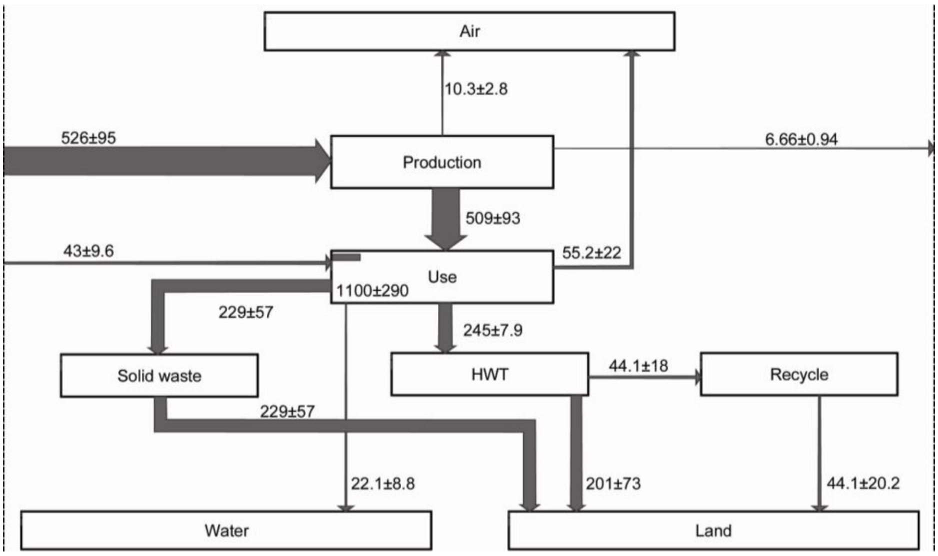


Fig. 2. Hg flow through FLs in Thailand, 2010.

Fig. 3 shows the Hg emission of FL use and disposal stage from the two sources: 1) HH, and 2) ICS. These results highlight that land was the largest repository of Hg from FL treatment. Around 562 kg of Hg was released to the environmental compartments, 84% to land, 12% to air, and the rest to water. Both of HHs and ICS released large amounts of Hg to land because all FL wastes were disposed of in landfills.

B. Uncertainty Analysis

In this study, probability distributions of the variables were calculated using Monte Carlo simulation with a sample size of 100,000. The results show that the 5% and 95% confidence interval for total Hg emission from FL use and treatment phases were 416 and 721 kg Hg/year, respectively (Fig. 4).

A parameter ranking shows that only two of twelve parameters were responsible for 95% of the uncertainty of Hg emitted in the environment. These parameters are *number of FLs produced* and *Hg content per domestic lamps*. To reduce the uncertainty of Hg released to the environment, these two parameters would have to be known better.

C. Sensitivity and Scenarios Analysis

The result of the sensitivity analysis showed the key parameters responsible for total Hg emission from FLs in Thailand. The most sensitive parameters are *number of FLs produced and Hg contained in domestic lamps,* and the minor sensitive parameters include *part recycle to landfill, number of FLs imported, and Hg contained in imported lamps.* For scenario analysis, the feasible sensitive parameters were selected. The following five scenarios have been set to reduce Hg emission from FL production, use and treatment in Thailand.

Scenario 1: Reducing Hg content in FLs

To reduce Hg consumption in FLs in the country, setting Hg-content limits will help protect customers by minimizing the amount of Hg in each lamp and thus potential exposure during use, handling, and subsequent treatment and disposal. According to the European Union (EU), the new standard of Hg in FLs was developed under the EU RoHS Directive. The maximum limit of 2.5 mg Hg was allowed in compact FLs (if less than 30 watts), and 3 mg Hg for modern linear T5 FLs (Triband phosphor, lifetime <25,000 hours) [25]. In addition, several reports from lighting companies and relevant organizations revealed that T5 FL is able to function with Hg content between 1.4 mg and 3.2 mg. [26]-[28]. In our scenario 1, we assumed a Hg content of 2.5 mg per lamp for all FL types.

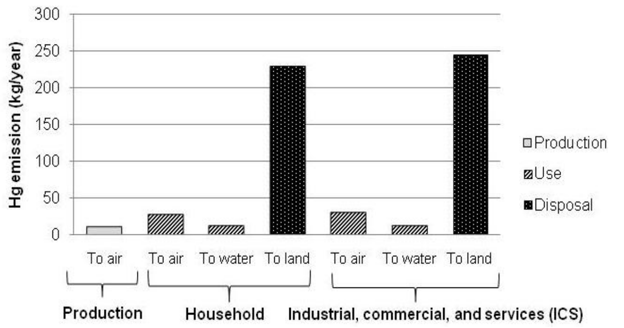


Fig. 3. Hg emission from fluorescent production, use and disposal phase in Thailand, 2010.

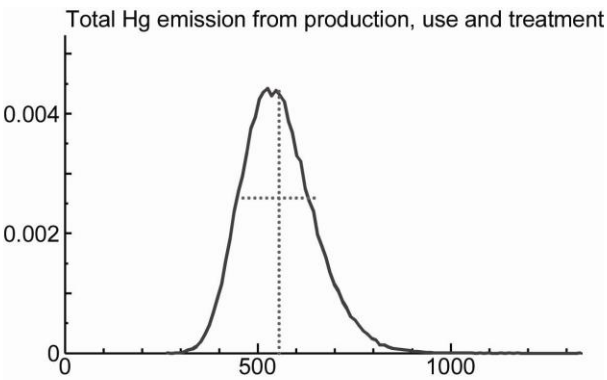


Fig. 4. Probability distribution of Monte Carlo simulation for total Hg emission from use and treatment phases (kg/y): the area under the curve is equal to 1; the curved line is the shape of total emissions and the dotted straight lines show the mean and standard deviations of this curve.

Scenario 2: Recycling Hg from FL wastes: 18% recycled from ICS FL waste and 0% from HH FL waste

Recycling of Hg from FL waste is one of the possible approaches for improving FL waste management in Thailand. As mentioned above, although Thailand has recycling plants for FL waste, phosphor powder containing Hg is disposed of in secure landfills. The available technology for Hg recovery from FL wastes has been applied in other countries such as Japan, and Canada [7], [29]. In accordance with this technology, we assumed that Thailand would upgrade the recycling plant with technology for recovering Hg from FL wastes. Also, we assumed that the achievement percentage of this potential would follow the current recycling rate of FL wastes from ICS and HH as described in section A of results and discussion.

Scenario 3: Recycling Hg from FL wastes: 50% recycled from ICS FL waste and 10% recycled from HH FL waste

The recycling rate of FL wastes from both ICS and HH was increased in this scenario when compared with scenario 2. In 2010, around 2.8 million households in Bangkok, (or about 14% of total HH in Thailand) [21]. If the local government of Bangkok (Bangkok Metropolitan of Administration - BMA) started collecting spent FLs from Bangkok households, this would allow a higher volume of FL wastes and Hg going to recycling plant for further proper hazardous waste treatment. We assumed that about 70% of spent FLs from Bangkok HHs are collected. Therefore, a 50% Hg recycling rate from ICS FL wastes, and 10% Hg recycling rate from HH FL waste in Thailand were assumed in this scenario.

Scenario 4: Replacing 30% FLs with light-emitting diode (LED) lamp

LED is a solid light bulb and a highly energy-efficient technology. This lamp type is Hg free, with potential long life, and little maintenance. LED lamps are commonly used to replace FLs in the USA [30]. In India, the use of LED was promoted since the first LED plant was established in 2010 [31]. In Thailand, the Electricity Generating Authority of Thailand (EGAT) has started to promote the use of LED in both government and household sectors in 2012 [32], [33]. The lamp manufacturing company predicted that the use of LED in Thailand will increase to 30% in 2015 due to its high efficiency and price decrease [34].

Scenario 5: Replacing 100% FLs with LEDs

With rapid performance improvements and dropping prices, LED lamps can replace all traditional bulbs. This scenario was set for the best case of Hg-free lighting sources in Thailand, assuming all FLs were replaced by LEDs.

Table I shows the results of scenario calculation. Setting the Hg-content limit at 2.5 mg per lamp can reduce total Hg consumption in FLs around 44% from the current situation (see scenario 1). This scenario can help to reduce Hg emission from production, use and disposal phase to all environmental compartments (air, water, and land). Scenarios 2 and 3 were set based on the existing FL waste management system in Thailand by varying the possible recycling rate of FL waste from ICS and HHs. In scenario 2, about 44 kg Hg from ICS waste will go to recycling plant and be recycled instead of disposal at landfills whereas a larger amount of Hg, estimated at about 145 kg, would be recycled in scenario 3. The result indicated that increasing the recycling rate of Hg in spent FLs from ICS and HH waste increased the potential reduction of Hg emissions to the environment from 8% to 26%. To achieve the goals of these two recycling scenarios (scenario 2 and 3), two issues need consideration. First, Thailand has no system to collect and separate municipal solid wastes and hazardous wastes from HH sources. This has to be started and implemented. Second, the current recycling plant for FL wastes in Thailand would have to add Hg recovery technology such as dry recovery type machine (Hg distillation), which is used in Japan. This technology recovers pure Hg from Hg emitted during the cutting and blowing processes of waste [7]. Replacing FLs with alternative LED (Hg-free) lamps was used for scenario 4 and 5. Replacing 30% FLs with LEDs can reduce total Hg emission around 167 kg/year (or 30% potential reduction) compared to the current situation. The highest potential reduction of Hg consumption from FLs is shown in scenario 5.

TABLE I: THE POTENTIAL REDUCTION OF MERCURY FROM SCENARIO ANALYSIS

Scenario	Description	Hg emission, kg (% potential reduction)			
		To air	To water	To land	Total
0	Current	65(0)	22(0)	474(0)	562(0)
1	Limit Hg content in FL (2.5 mg/lamp)	36(44)	12(44)	264(44)	312(44)
2	Recycle FL waste 18% ICS[1] + 0% HH[2]	65(0)	22(0)	430(9)	517(8)
3	Recycle FL waste 50% ICS[1] + 10% HH[2]	65(0)	22(0)	329(31)	416(26)
4	Replace 30% FL with LED	46(30)	16(30)	334(30)	395(30)
5	Replace 100% FL with LED	0(100)	0(100)	0(100)	0(100)

ICS: Industry, commercial, and services

HH: Household

Although scenario 3 and 4 show similar percentage of reduction of the total emission to the environment, a measure to reduce Hg flows by replacing FL with LEDs in scenario 4 is more feasible than recycling Hg from FL wastes in scenario 3. This is due to the implementation of FL waste collection/separation system at source and the installation of Hg recovery technology as described above. According to Manager Online [35], although LED prices are currently nine times higher than FLs, the price of LED will gradually decrease in the near future.

Since currently the rate of LED use in Thailand is limited due to high price constraint, and FL is still widely used across the country, the current potential reduction is to promote LED use and to reduce Hg content for each lamp (combining scenarios 1 and 4). This would result in a possible reduction of 61%.

IV. CONCLUSION

The use of a MMFA model has allowed us to study the system and to derive scenarios. In this study, the assessment of Hg flows through FLs in Thailand using MMFA has provided a better system understanding. This has led to the suggestion of the possible measures to reduce Hg pollution from FL production, use and disposal in Thailand.

In 2010, the total amount of Hg imported to Thailand for FL production and in FL products was around 569 kg whereas only 7 kg was exported in FL products. Hg was stocked in FL use at around 1,100kg, about double of imported Hg. All Hg from household FL waste was sent to sanitary landfills while Hg in FL wastes from ICS was sent to HWT for landfilling, or recycling. At the recycling plant, Hg was not recovered from FL wastes but was disposed of at secure landfills. Hg is emitted from FL during production, use, and disposal phase. It was estimated that total Hg emission from FL was about 562 kg, with 84%, 12%, and 4% go to land, air, and water, respectively.

To achieve the highest Hg potential reduction, replacement of all FLs with LEDs is recommended in this study. In addition to replacement, setting Hg-content limit at 2.5 mg Hg per lamp shows a high potential reduction of Hg emissions.

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