博士論文（要約）

Analysis of material flow and environmental and resource impact for strategic management of end-of-life electrical and electronic equipment in China

(中国における使用済み電気・電子製品の戦略的管理のための物質フローと環境・資源影響分析)

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September 2013

End-of-life electrical and electronic equipment (EoL EEE) issue is regarded not only as an emerging environment problem but also as a part of resource management strategy. EoL EEE contains valuable materials including precious metals such as copper, gold and silver etc. as well as potential harmful substances such as lead and mercury and so on. Therefore, EoL EEE should have negative impacts on both nature environment and human health if it is unprocessed or processed without adequate controls on one hand. On the other hand, adequate and efficient recovery of valuable materials contained in EoL EEE would provide a benefit on resource availability.

China is one of the largest emerging electronic market regions in the world of global manufacturing, production and sales market point due to their cheap labor and huge population. The large possession gathering technical innovation in EEE, eventually, has accelerated generation of EoL EEE. However, the large amounts of EoL EEE have still been informally collected and treated in China. The informal treatment areas where EoL EEE is dumped and dismantled illegally are causing an increasing environmental and human health concerns. Nevertheless, there exists no well- designed EoL EEE management system in current China. With increasing amounts of EoL EEE being generated, well- designed EoL EEE management not only contributes to controlling on contaminants caused by illegal or immature recovery process but also contributes to resource utilization in significance demand in current and future. Therefore, the win-win strategy of management of EoL EEE has become of concern.

At present, it is significant to do quantitative analysis on EoL EEE capturing how much it will be generated and how much materials and substances it contains as the basis of information for managing EoL EEE by both product and substance levels in China. So far, several studies have also estimated the amount of EoL EEE in China. However, in those existing studies, there remain some problems. First, simple assumptions have been applied to the lifespan of EEE which is one of the most important parameters influencing the final result. Second, dynamic (year-by-year) changes in lifespans of EEE have not been considered in a calculation scheme. Third, the longer trend of predicted result is preferable compared to those of near current years in most of the past studies. The most important point is that, up to now, there exists no literature that describes substance flows contained in EoL EEE in China.

As far as policies and legislations are concerned, however, China has no experience in how to manage EoL EEE recycling when compared with developed countries. In addition, several economic and social factors had led to that EoL EEE flow in China was sophisticated and far from understands. Furthermore, the treatment processes used to be applied in informal yards as primitive pyro and hydro metallurgical processes without any controls, such as open burning, open dumping and acid leaching etc., which should cause server environmental pollutions. Even in formal treatment sides, the business scale, treatment method, recycling efficiency and working environment are various. There is as yet, no regulation to standardize these issues aforementioned. Addressing current problems of management of EoL EEE, it is urgent to consider that how to improve and standardize the recycling and recovery processes, how to restrain the informal treatment processes of EoL EEE and how to make strategic planning for management of EoL EEE, which should contribute to the growing crisis in resource shortage and preventing the environmental contaminants.

Therefore, the goal of this study is supporting decision-makers to develop strategic policies for management of EoL EEE including plans for appropriate capacities of recovery and treatment facilities to meet the requirement of proper waste treatment as well as to maximize secondary resource recovery. Specifically, the objectives and methodologies of this study include:

- To estimate possession and generation of EoL EEE and forecasting their future trend in China. A model estimation and product flow analysis (PFA) were applied.
- To evaluate hazardous and valuable substances contained in EoL EEE in China. The method used was substance flow analysis (SFA).
- To explore current status of EoL EEE management along with EoL EEE flow in China. Methodologies used were legislation, regulation and literature review and field survey.

- To set EoL EEE recycling and treatment scenarios and assess on them as from environmental and resource aspects. Life cycle impact analysis (LCIA) was applied in this part.

System boundary consists of pre-disposal and post-disposal phase in the study. Pre-disposal phase include the stages as from new product start to be consumed to that no longer be used by consumer. Post-disposal phase include the stages as recycling, further treatment, incineration, melting and so on. Among the items being recycled, household appliances (HAs) play a vital role due to the characteristics of, such as, large volumes, persistent threat to the environment if no proper disposal undertaken, as well as the generation of some hazardous derivatives. Thus, television set (TV), personal computer (PC), air conditioner, washing machine and refrigerator were chosen to the targets of pre-disposal phase. EoL TV and PC were targeted in post-disposal phase. Besides, 16 metals were selected for SFA, which are common metals such as aluminum (Al), copper (Cu), iron (Fe), tin (Sn), zinc (Zn), nickel (Ni) and lead (Pb), less common metals such as barium (Ba), bismuth (Bi), cobalt (Co), antinomy (Sb), mercury (Hg) and strontium (Sr), precious metals such as silver (Ag), gold (Au) and palladium (Pd). These substances are contained in TV sets, and controversial as environmental and resource viewpoints.

Based on past statistical data and other available data as well as model estimation, the average maximum possession amounts have been predicted that 215 and 167 units of TV, 223 and 103 units of air conditioner, 98 and 50 units of PC, 102 and 102 units of refrigerator as well as 103 and 102 units of washing machine owned by 100 urban and rural households respectively. In addition, the total possession amounts of HAs will keep increasing in next 20 years. Especially, air conditioner and PC do not reach their saturation of ownership by household. The total possession amount of 5 kinds of HAs will keep increasing trend in next 20 years. It has been estimated that the total possession amounts in 2030 (3.1 billion units) will be 2 times higher than that in 2010 (1.6 billion units). On the basis of estimation, the average lifespans of color TV, refrigerator, washing machine, air conditioner and PC were 16 years, 14 years, 10 years, 6 years and 4 years respectively in the past years. The total generation of EoL five kinds of HAs will be 314 million units by 2030, which is 2.5 times higher than that in 2010; Cumulatively over 5.1 billion units of EoL five types of HAs will be generated during the year 2010- 2030.

Under the assumption of dynamically decreasing lifespan of PCs and TVs, the generation of EoL 5 types of HAs cumulatively over 5.4 billion units in the year 2010- 2030, which is 6% higher than previous result; in case of TV, it can be calculated that one unit (year) decrease or increase in lifespan, would cause approximately ±6% fluctuation of annual obsolescence amount in average comparing to previous result; the cumulative generation of EoL TVs will range from 728-770 million units in 2010-2030, depending different scenarios for lifespan (dynamic decrease in 16~14, dynamic increase in 16~18).

On the basis of SFA, the main contributor in ferrous, aluminum and copper contents contained is metallic parts such as metallic housing and coil etc. in obsolete TVs. Duo to copper, lead and nickel contents in FPD TV are smaller than CRT TV, gathering CRT TV will be replaced by FPD TV in the near future, the total trend of them will decline until 2030 compared to others. The main contributor in tin, nickel and zinc contents contained is printed circuit board (PCBoard) in obsolete TVs. The tin and zinc contained in PCBoard of FPD TVs are larger than that in CRT TVs in the future. The main contributor in lead content contained in obsolete TVs is CRT funnels. In addition, less common metals except mercury (Hg) and common metals such as copper (Cu), nickel (Ni) and Lead (Pb) will have a trend of decrease, whereas other common metals such as iron (Fe), aluminum (Al), tin (Sn) and zinc (Zn) as well as precious metals will have a trend of increase in their content of obsolete EoL TV sets in 2015-2030.

As one of the urban mine, EoL TVs present high potential to deal with resource shortage. The precious and less common metals such as silver, gold, palladium, copper, bismuth and antinomy stocks in EoL-TVs will be 256, 190, 167, 455000, 410 and 22180 ton respectively, whereas, the potential harmful metal such as mercury stock will be 40 ton at the end of 2030 . Under the assumption of different scenarios of future market share between CRT and FPD TV, maximum stocks of lead, barium, antinomy and strontium at the end of 2030 will be 13%, 10%, 4% and 13% higher than precious result. In addition, tin, copper, iron and gold contain relative high resource cost compared with other metals, thus recovery and recycling them from EoL TVs might be one of the business opportunities.

When exploring current status associated with EoL EEE management, the current challenges can be summarized as, first, the government is trying to apply Extended Producer Responsibility (EPR) that will be one of the challenges to managing EoL EEE in next stage. Second, the registered formal recyclers whose treatment facilities, environmental standards and recycling efficiencies still varying in certain degree, are now actively present in EEE manufacturer dense regions. Finally, manual dismantling and primitive recycling methods is allocated in the informal sector in comparison to the automated processes in formal sectors for recycling. In addition, according to LCIA results of three different treatment options, the advanced formal treatment option (option 2-a) provides the best value in alleviation of social cost for mining virgin materials. By constraint, informal treatment option (option 1) provides the worst value in alleviation of social cost for mining virgin materials. Further, the processes in informal treatment present high potential environmental impact and influence to human health. Therefore, two kinds of strategies might be able to deal with increasing concerns on environment impacts coming from improper treatment of EoL EEE. One is that mandatorily convert informal treatment processes to formal one. Other is that to improve informal treatment processes by various ways such as leading-in developed machinery equipment and subsidy support by government.

The huge amounts of EoL TVs will be generated in next 20 years whereas the relative few amounts of EoL HAs sets have been discarded before 2010. Thus, which duration to covert or improve the informal treatment to formal become considerable. The results of scenario analysis present that totally convert informal (option 1) to formal (option 2-a) in 2013-2020 might be one of options for strategic management of EoL EEE duo to their maximum value in both alleviation of social cost necessitated by extracting raw materials and prevention of environmental contaminants.

There are some limitations in this research which can be suggested for conducting similar study and improvement for future research. First, the EoL EEE includes various items. Other EoL EEE items such as mobile phone and small household appliances etc. also play a vital role in viewpoint of environmental and resource aspects. Second, inventory data of the recycled materials which contribute to metal depletion (MD) as first- priority item were used to evaluate resource availability from the positive environmental impact. Meanwhile, the negative environmental impact analysis has been done only to a limited extend in this study duo to data availability. Therefore, more detailed and concrete environmental impact analysis in terms of other outputs such as leachate, bottom ash, chemical liquid, waste water and particle should be required for further study.