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Watch more, waste more? A stock-driven dynamic material flow analysis of metals and plastics in TV sets in China

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ABSTRACT

The growing generation of waste electrical and electronic equipment (WEEE) in developing countries has attracted increasing attention due to its potential health and environmental impacts and high recycling potentials. For example, along with the rapid economic development, China has been experiencing a sharp increase in the production and use of TV sets and a quick transition from old fashion cathode ray tube (CRT) ones to flat panel display (FPT) ones. Understanding such dynamics would be important for predicting future WEEE generation. In this article, we developed a dynamic (from 1992 to 2040), bottom-up (TV sets by module by material), and stock-driven (using future possession as a driver) material flow analysis model to investigate the amount of metals and plastics embodied in obsolete TV sets in the future. We found that the total generation of obsolete TV sets in China will reach 142 million units by 2040, in which FPD TV sets contribute more after they started to dominate the market after 2009. These growing obsolete TV sets would mean potentially large amount of embodied materials that can be recycled. While most of the embodied precious metals (e.g., gold, silver, and palladium), common metals (e.g., iron, aluminum, zinc, and tin), toxic metals (e.g., mercury, barium, and antimony), and plastics will increase in future, copper and nickel show a first decrease then increase trend, and lead will be gradually phased out in obsolete TV sets. Our results could help inform waste management and recycling strategies and relevant decision makers (e.g., governmental agencies, manufactures, and recyclers) in the TV sets sector in China. Such a stock-driven and bottom-up approach can also be used for other e-waste issues and other countries.

1. Introduction

The recent decades have seen a growing focus on the recycling of resources from waste electrical and electronic equipment (WEEE) worldwide, because WEEE recycling provides potential secondary resources that help relieve pressures on primary resources, environmental sustainability, and human health (Scruggs et al., 2016; Ruan et al., 2016; Huang et al., 2016; Shi et al., 2016). In addition, the recovery of resources from WEEE could also provide job opportunities for people and lead to large economic gains, such as precious metals (Oguchi et al., 2011; Charles et al., 2017), plastic (Martinho et al., 2012; Santella et al., 2016), and glass (Gu et al., 2016). This is particularly important for China, the world's largest developing country with rapid economic growth and large consumption of resources (Wang et al., 2017).

China's home appliance industry (usually referring to TV sets, washing machines, refrigerators, air conditioners, and computers in China) has been greatly developed in the past decades. For instance, the production of TV sets and refrigerators reached 145 and 80 million units in 2015, meaning an increase of nearly 74% and 168% comparing to ten years ago (NBSC, 2015). The amount of WEEE is expected to increase further following the growing production of household appliances. However, China has not yet established a perfect system of e-waste recovery and treatment, and large amounts of e-waste are still being improperly collected and treated (Wang et al., 2013). Therefore, the understanding of future WEEE generation and recycling potentials through urban mining is very important for sustainable resource, waste, and environmental

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management.

Material/substance flow analysis (MFA/SFA) is a widely used method for forecasting WEEE generation (both quantity and quality), which can consequently help decision makers for successful waste and environment management (Agamuthu et al., 2015; Parajuly et al., 2017; Habuer et al., 2014). In recent years, various MFA/SFA models have been developed for investigating e-waste generation and management in China (Lu et al., 2015; Zhang, 2009; Duan et al., 2016; Zhao et al., 2016; He et al., 2006; Zeng et al., 2016), particularly for obsolete home appliances such as mobile phones (Habuer et al., 2014; Xu et al., 2016) and TV sets (Song et al., 2012). However, these existing studies suffer from two main shortcomings: (i) They are largely based on projected sales for future scenarios of e-waste generation. Many studies have already shown that stocks may behave more robust than flows in long-term mass balance models (Liu et al., 2012; Pauliuk et al., 2012; Hatayama et al., 2010), and this has not yet been used in the WEEE study. (ii) They usually address different categories of WEEE as a total and do not have a resolution on the technology share and product component, which may hinder a detailed understanding of recycling potentials of WEEE.

In this study, we aim to address these gaps by developing a bottom-up and stock-driven dynamic material flow analysis model to investigate the future use and waste generation of different modules of TV sets in China and their embodied metals and plastics.

2. Materials and methods

2.1. System definition

The life cycle of TV sets and embodied material flows are shown in a system definition in Fig. 1. The spatial boundary of this study is mainland China and the temporal boundary is the period from 1992 to 2040. The overall system is divided into two parts: product level and substance level. At the product level, four stages of the TV set flows were considered, i.e., production, sale, use/storage, and waste management. At the substance level, the embodied metals and plastics of different components of the obsolete TV sets were considered, and the amount of the same type of metals and plastics (referred as S in Fig. 1) were then aggregated.

2.2. Dynamic material flow analysis of TV sets

2.2.1. Estimation of the historical sales and domestic possession of TV sets

The historical domestic sales of TV sets were estimated based on domestic output/production, import and export, and market stock (MStock) change (which was assumed to be 0 in the simulation due to lack of data), as shown below.

$$\text{Domestic sales } S(t) = \text{Domestic output}(t) + \text{Import}(t) - \text{Export}(t) + \text{MStock}(t-1) - \text{MStock}(t) \quad (1)$$

Based on the product life cycle theory (Habuer et al., 2014), the future possession of TV sets in urban and rural regions was predicted using logistic function given in Eqs. (2) and (3) (Tasaki et al., 2001; Liu et al., 2006; Habuer et al., 2014), and the total domestic possession was calculated using Eq. (4):

$$\overline{P}_u(t) = \frac{\overline{P}_{\max\_u}}{\left[1 - \alpha_u \cdot e^{-\beta_u (t - t_0)}\right]} \quad (2)$$

$$\overline{P}_r(t) = \frac{\overline{P}_{\max\_r}}{\left[1 - \alpha_r \cdot e^{-\beta_r (t - t_0)}\right]} \quad (3)$$

$$P(t) = \frac{\overline{P}_u(t)}{100} \cdot H_u(t) + \frac{\overline{P}_r(t)}{100} \cdot H_r(t) \quad (4)$$

where $\overline{P_u}(t)$ and $\overline{P_r}(t)$ are the amounts of the average possession of TV sets per 100 urban and rural households in year t, which are available from NBSC (National Bureau of Statistics of the People's Republic of China). $\overline{P}_{\max\_u}$ and $\overline{P}_{\max\_r}$ are the maximum levels of the average possession amounts of TV sets per 100 households in urban and rural regions. α_u, α_r β_u and β_r are parameters: α_u and α_r are equal to $-\exp\{\beta_u(t_{1/2} - t_0)\}$ and $-\exp\{\beta_r(t_{1/2} - t_0)\}$, where t_0 is the starting year for calculation and $t_{1/2}$ is the year when the average possession amount reaches half of the maximum; β_u and β_r indicate the growing speeds of the product possession, and they are based on the past trend of possession rates of urban and rural households that can be calculated by regression of collected statistics data of $\overline{P_u}(t)$ and $\overline{P_r}(t)$ in the years 1992–2012. $P(t)$ is the total possession amount of TV sets in year t; $H_u(t)$ and $H_r(t)$ indicate the numbers of urban and rural householdsin year t, which are available from NBSC and the future amount was calculated by extrapolating regression of the past trend in 1992–2012. According to previous research (Tasaki et al., 2001; Zhang et al., 2011), the maximum level of the average possession of TV sets in urban areas have been estimated to be 216 units per 100 households, and likewise those maximum levels in rural areas have been estimated to be 167 units per 100 households.

2.2.2. Prediction of the future generation of obsolete TV sets

The amount of domestic generation of obsolete TV sets in year t, $G(t)$, depends on the lifespan distribution of TV sets and the sales amount of TV sets before a period of i years. The following Eq. (5) was used to calculate the domestic generation of obsolete TV sets in year t:

$$G(t) = \sum_{i=1}^{t} [S(t-i) \cdot f(i)] \quad (5)$$

Where, $S(t-i)$ is the amount of domestic sales before a period of i years; $f(i)$ is the function of lifespan distribution, which was obtained by using the accumulated Weibull distribution function as expressed in the following Eq. (6). Here, $W(i)$ indicates the accumulated Weibull distribution function.

$$f(i) = W(i) - W(i-1) \quad (6)$$

The estimation of the lifespan of TV sets requires applying accumulated Weibull distribution function$W_t(y)$, as expressed in Eq. (7) (Tasaki et al., 2001, 2004; Oguchi et al., 2006, 2008).

$$W_t(y) = 1 - \exp\left\{ - \left[\frac{y}{y_a}\right]^b \cdot \left[\Gamma\left(1 + \frac{1}{b}\right)\right]^b \right. \quad (7)$$

Here, y is the lifetime of each TV set; y_a is the average lifespan of TV set; b is a parameter of Weibull distribution, which indicates the deviation of distribution; Γ is the gamma function. The parameter b of Weibull distribution function was already estimated in some previous studies (Tasaki et al., 2001; Oguchi et al., 2006, 2008) as a range of 1.7–3.3 for the electronic durable goods. In this analysis, according to Oguchi et al. (2006), the value of parameter b of TV sets is set as 3.1, and based on previous research (Yang et al., 2008; He et al., 2006; Liu et al., 2006; Zhang et al., 2012; Habuer et al., 2014), the value of y_a of TV sets is set as 10.6 y.