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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.

**Key words:** Substance flow analysis; Stock in use; Obsolete TV sets; WEEE recycling; Waste management
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 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.

![Fig.1. Overall System boundary of the article](image-url)
• Module wise, TV sets can be divided into two main types: Cathode Ray Tube (CRT) TV set and Flat Panel Display (FPD) TV set. CRT TV set is a traditional type which is based on a vacuum tube containing one or more electron guns (a source of electrons or electron emitter) and a fluorescent screen used to view images. FPD TV set is smaller and lighter and consists of four sub-types: Liquid Crystal Display (LCD), Plasma Display Panel (PDP), Organic Light Emitting Display (OLED), and Surface-conduction Electron-emitter Display (SED).

• Component wise, a TV set consists of shell (including front and rear cover), speaker, and circuit board. In general, the inside structure is diverse because different technologies are applied in different types of TV sets. For instance, old-fashioned CRT TV sets use picture tubes, and LCD TV sets apply liquid crystal display panel, which comprises a fluorescent tube, a light guide plate, a polarizing plate, a filter plate, a glass substrate, an alignment film, a liquid crystal material, and a thin mode transistor.

• Material wise, TV sets are mainly composed of plastics and metals, both of which have huge recycling potentials. Metals constitute a relatively large weight fraction in the circuit board of TV sets (both CRT and FPD). These metals can be grouped as precious metals (i.e., gold (Au), silver (Ag), and palladium (Pd)), common metals (i.e., copper (Cu), iron (Fe), aluminum (Al), zinc (Zn), tin (Sn), and nickel (Ni)), and toxic metals (i.e., lead (Pb), mercury (Hg), barium (Ba), and antimony (Sb)). The substance concentrations of metals and plastics differ by types and
modules of TV sets.

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.

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

$$\bar{P}_u(t) = \frac{\bar{P}_{\text{max},u}}{1 - \alpha_u \cdot e^{-\beta_u(t-t_0)}}$$  \hspace{1cm} (2)

$$\bar{P}_r(t) = \frac{\bar{P}_{\text{max},r}}{1 - \alpha_r \cdot e^{-\beta_r(t-t_0)}}$$  \hspace{1cm} (3)

$$P(t) = \frac{\bar{P}_u(t)}{100} \cdot H_u(t) + \frac{\bar{P}_r(t)}{100} \cdot H_r(t)$$  \hspace{1cm} (4)

where $\bar{P}_u(t)$ and $\bar{P}_r(t)$ 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). $\bar{P}_{\text{max},u}$ and $\bar{P}_{\text{max},r}$ are the maximum levels of the average possession amounts of TV sets per 100 households in
urban and rural regions. \( \alpha_u, \alpha_r, \beta_u \) and \( \beta_r \) are parameters: \( \alpha_u \) and \( \alpha_r \) 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; \( \beta_u \) and \( \beta_r \) 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 \( \bar{P}_u(t) \) and \( \bar{P}_r(t) \) 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 households in 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 \( t \):

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

(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.

\[
f(i) = W(i) - W(i - 1)
\]  

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).

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

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; \( \Gamma \) 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.

Based on the previous equations, the lifespan distributions of TV sets \( f(i) \) were presented in Fig.2, which represents the obsolete rate after \( i \) years when the TV sets came into use. Fig. 2 shows that the obsolete rate would peak in the ninth year after
the TV sets came into use.

![Fig.2. Lifespan distribution of TV sets in China](image)

**Fig.2.** Lifespan distribution of TV sets in China

The future domestic sales $S_f(t)$ were then estimated by Eq. (8)

$$S_f(t) = P(t) - P(t - 1) + G(t)$$  \hspace{1cm} (8)

2.2.3. Metals and plastics in obsolete TV sets

$SC_{TV}$ is the substance concentration of an obsolete TV set in year $t$ which can be calculated using Eq. (9). Here, $W_m(i)$ is the weight of module $i$ of obsolete TV set and $SC_m(i)$ is the substance concentration of module $i$.

$$SC_{TV} = \sum_i W_m(i) \times SC_m(i)$$  \hspace{1cm} (9)

The weight of module $i$ of an obsolete TV set in year $t$ can be calculated using Eq. (10) (Habuer et al., 2014). Here, $A_{TV}$ is amount of obsolete TV set; $\bar{W}_{TV}$ is average weight of obsolete TV set; $M_c$ is module composition.

$$W_m(i) = A_{TV} \times \bar{W}_{TV} \times M_c$$  \hspace{1cm} (10)
2.3. Data sources and uncertainty analysis

2.3.1. Production, import, and export of TV sets

China has already become the world’s largest manufacturing base of electronic products (Song et al., 2012). The domestic output, import, and export data of TV sets in China from 1992 to 2014 are taken from NBSC and GAC (General Administration of Custom of the People’s Republic of China) (Fig. 3).

![Graph showing domestic output, export, and import of TV sets in China, 1992-2014.](image)

**Fig.3.** Domestic output, export, and import of TV sets in China, 1992-2014.

2.3.2. Possession of TV sets

The average possession of TV sets per 100 households in China was taken from NBSC (NBSC, 2015). Note that the data of urban households only include color TV sets, and the data of rural households include both color TV sets and black-and-white TV sets. Fig. 4 shows a small difference for the possession between urban and rural households and a generally increasing but gradually leveling-off trend since 2004.
Fig. 4. The average possession of the TV sets in urban and rural China, 1992-2012.

Figure 4 shows that the growing speed of TV sets possession in urban and rural region are 5.1% and 6.2% from 1992 to 2012, respectively. For equations (2) to (4), $\beta_u$ is 0.051, $\beta_r$ is 0.062, $\alpha_u$ is -1.50, and $\alpha_r$ is -1.28.

2.3.3. Market share, substance concentration, and average weight of TV sets

The market share of CRT and FPD TV sets was collected from ECCIIY (Editorial Committee of China Information Industry Yearbook, 1992-2015) and CIA (China Information Almanac, 1992-2015). Fig. 5 shows that the CRT TV sets dominated China’s domestic TV sets market before 2008. However, FPD TV sets started to penetrate the market since 2005 and grew drastically thereafter. Their market share exceeded that of CRT TV sets for the first time in 2009 and accounted for 99% of the total already in 2014. Consequently, CRT TV sets are assumed to be phased out after 2015.
Fig. 5. Market share of FPD and CRT TV sets in China, 1992-2040.

Data on the substance concentration of different TV sets were taken from literature (see Table 1). The average weight of CRT and FPD TV sets was set as 23.9 kg and 20.8 kg (Habuer et al., 2014). Since the market share of PDP, OLED, and SED TV sets are very small in China, we used the same data on average weight, module composition, and substance concentration of LCD TV sets to analyze all types of FPD TV sets.

Table 1. Substance concentrations in different types of TV sets

<table>
<thead>
<tr>
<th></th>
<th>CRT TV set</th>
<th>FPD TV set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Panel</td>
<td>Funnel</td>
</tr>
<tr>
<td>Precious metal</td>
<td>Gold</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>Silver</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>Palladium</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>Iron</td>
<td>0.11%</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>1.10%</td>
</tr>
<tr>
<td></td>
<td>Zinc</td>
<td>0.31%</td>
</tr>
<tr>
<td></td>
<td>Tin</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>Nickel</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>Lead</td>
<td>0.01%</td>
</tr>
<tr>
<td>Toxic metal</td>
<td>Mercury</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>Barium</td>
<td>7.90%</td>
</tr>
<tr>
<td></td>
<td>Antimony</td>
<td>0.26%</td>
</tr>
<tr>
<td>Plastic material</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Data source: Oguchi et al., 2011; Tasaki et al., 2007; Ha et al., 2009; Habuer et al.,
2014. N.A.: not available; PCB: Printed circuit board; CCFL: Cold cathode fluorescent lamps.

2.3.4. Uncertainty analysis

Data used in our model were collected from various sources such as literature, governmental statistics, and industry market forecast, and they unavoidably bear uncertainties. We have estimated the range of the key parameters, i.e., average lifespan, total weight, substance concentration, and market share, in Table 2, as a qualitative understanding of their potential ranges. Since the weight of TV sets is proportional to the simulated results of obsolete TV sets and the change of market share of TV sets is identical (i.e., FPD TV sets account already 99% of the market in 2014), we chose the remaining two most uncertain parameters, i.e., substance concentration and average lifespan, for further quantitative uncertainty analysis. We have additionally considered the impact of the maximum level of average possession on our results, since it is based only on literature values.
Table 2. Range of parameters used in our model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average lifespan</td>
<td>8-16 y</td>
<td>The value was changed with estimated method and time</td>
</tr>
<tr>
<td>Weight</td>
<td>10-50 kg</td>
<td>Model, manufacturer, technology, and material choice could all affect the weight of TV sets</td>
</tr>
<tr>
<td>Gold</td>
<td>0.005%-0.016%</td>
<td>Substance concentration could change a lot as technology changes in the future, and the value is different in different types TV sets.</td>
</tr>
<tr>
<td>Silver</td>
<td>0.012%-0.0189%</td>
<td></td>
</tr>
<tr>
<td>Palladium</td>
<td>0.002%-0.012%</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>3%-7.2%</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>3.59%-5.11%</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>2%-14.172%</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>0.91%-2.01%</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>1.8%-2.76%</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>0.032%-0.85%</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.067%-22.91%</td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>0.0002%-0.035%</td>
<td></td>
</tr>
<tr>
<td>Barium</td>
<td>0.0315%-8.46%</td>
<td></td>
</tr>
<tr>
<td>Antimony</td>
<td>0.0094%-0.73%</td>
<td></td>
</tr>
<tr>
<td>Plastic</td>
<td>20.6%-27.3%</td>
<td></td>
</tr>
<tr>
<td>Market share</td>
<td>N.A. b</td>
<td>The possibility of market share change of FPD and CRT TV set is quite low, but new type of TV sets could be introduced into market with development of technology.</td>
</tr>
</tbody>
</table>

Data source: Habuer et al., 2014; Song et al., 2015; Singh et al., 2016. Note: a Informed estimate. b Change was not considered due to (i) the recent development is identical and (ii) lack of knowledge on new technology and market development.

3. Result and discussion

3.1. Projected possession and generated obsolete TV sets in China

Trend analysis of average possession of TV sets per 100 urban and rural households through applying Eq. (2) and (3), respectively, are shown in Fig. 6 (a). In urban area, the amount of actual average possession of TV sets per 100 urban households was less than the predicted amounts between the years 1992 and 1996; the actual values were higher than predicted values from 1997 to 2008 and then gradually overlapping with
predicted afterwards. In rural area, the amount of actual average possession of TV sets per 100 rural households was less than the predicted amount between the years 1992 and 1995 and the actual values were higher than predicted values from 1996 to 2005 and then gradually overlapping with predicted values afterwards.

The total domestic possession amounts of TV sets through applying Eq. (4) was shown in Fig.6 (b). The data of total domestic possession between 1992 and 2012 are calculated by actual values, while data between 2013 and 2040 are predicted values. The annual total possession of TV sets has a general uptrend, and reaches 1964 million units in 2040, approximately 7 times higher than that of 1992. With the improvement of living standard, the average possession amount of a household increases from 0.6 units in 1992 to 1.8 units in 2040.

Fig.6. Average possession of TV sets per 100 urban and rural households (a) and total domestic possession of TV sets (b)
The total generation of obsolete TV sets (Fig. 7a) will reach 142.09 million units in 2040, which is approximately 4.2 times higher than that in 2012. This would mean an accumulative amount of obsolete TV sets of over 2,562 million units from 1992 to 2040.

![Fig. 7. The total amount (a) and weight (b) of obsolete TV sets in China.](image)

### 3.2. Metals and plastics in obsolete TV sets

The weight of different types of obsolete TV sets was estimated and shown in Fig. 7(b). The domestic obsolete TV sets contained only CRT TV sets before 2006, and in 2012, the obsolete weight of CRT TV sets reached peak at 723 kt, then it began to decrease gradually. The obsolete FPD TV sets appeared in 2006, and their weight (498 kt) reached almost the same level of CRT TV sets (516 kt) in 2017. In 2040, the weight of FPD TV sets will be 4.4 Mt and the corresponding accumulative weight will be 57.9 Mt from 1992 to 2040. Therefore, obsolete FPD TV sets will become the main part of obsolete TV sets in future.
Basing on the substance concentration data in Table 1, the substance of metallic materials and plastic material in obsolete TV sets per year can be calculated and shown in Fig. 8 - Fig. 11.

**Fig. 8.** Amount of precious metals in obsolete TV sets

**Fig. 9.** Amount of common metals in obsolete TV sets
The substance concentrations of precious metals in PCBs of FPD TV sets are higher than in CRT TV sets, thus the embodied gold, silver, and palladium increase in obsolete FPD TV sets as time goes. Regarding the common metals, the embodied iron, aluminum, zinc, and tin tend to increase owing to growing generation of obsolete TV sets, for instance the weight of iron in FPD TV sets will reach 225.3 kt in 2040.

However, other common metals such as copper and nickel show a first decreasing and then increasing trend, because the substance concentrations of copper and nickel in FPD TV sets are lower than in CRT TV sets (for instance, the weight of copper in
FPD TV sets (47.2 kt) in 2040 is still lower than that in CRT TV sets (52.03 kt) in 2012). Regarding the toxic metals, the weights of barium and antimony increase with the generation trend of obsolete TV sets. Mercury was widely used in CCFLs contained in FPD TV sets, and its weight will reach 1.5 kt in 2040. With the increasing recognition of its adverse environment impact, the embodied lead has declined in FPD TV sets compared to CRT TV sets and will be gradually phased out in future. The substance concentration of plastic is higher in CRT TV sets than in FPD TV sets, thus the total weight of plastic in obsolete TV sets will reach 1.2 Mt in 2040.

3.3. Uncertainty analysis

The average lifespan, weight, substance concentration, market share, and the maximum level of average possession of TV sets are main parameters in our model and all could lead to uncertainty of results. Substance concentration data are taken from difference literature and may bear high uncertainty; and they may also change in the future as technology develops. Such temporal changes are very difficult to be considered quantitatively due to lack of information. Instead, we take the estimated ranges (see Table 2) for uncertainty analysis. Fig. 12 (a) shows results of the examples of copper, iron, and aluminum from 1992 to 2040 (we set the average weight of TV sets as 22.4 kg). There was a wide gap between the high level and low level of substance concentrations, for instance, the high level of substance concentrations of copper, iron and aluminum are 53.76, 31.88 and 158.72 times, respectively, as much as low level in 2040.
Fig. 12. Uncertainty analysis of substance concentrations (a) (example of Cu, Fe, and Al) and the impact on generation of obsolete TV sets with one-year change of average lifespan (b) and the impact on generation of obsolete TV sets with the 10% change of maximum level of the average possession of TV sets (c). We used a Weibull distribution for the lifespan of TV sets, as it is found the most likely distribution for electronics (Habuer et al., 2014; Gu et al., 2016; Parajuly et al., 2017). This was kept the same in the uncertain analysis and we only changed the average lifespan. We found that one-year increase or decrease of the average lifespan...
would cause an approximately ±11% fluctuation of the annual obsolete amount of TV sets (Fig. 12b).

The maximum level of average possession of TV sets is based on literature values due to lack of empirical data. As shown in Fig. 12c, we found that a 10% increase or decrease of the maximum level of average possession would cause an approximately ±6% fluctuation of the annual obsolete amount of TV sets.

3.4. Policy implications and suggestions

Our results show that the possession of TV sets in both urban and rural China will continue increasing in the future, but the growth rate will be decreased. Total possession of TV sets by 2040 will be two times higher than that of 2012, resulting in potentially large amount of obsolete TV sets and embodied materials. FPD TV sets began to penetrate in the market from 2005 and have dominated the market after 2009. It is estimated that 21.58 million units of CRT TV sets and 23.94 million units of FPD TV sets were discarded in 2017, and the accumulative amounts of obsolete TV sets will be over 2.8 billion units from 2017 to 2040, in which the main contributors will change to FPD TV sets. The simulated results of embodied materials in obsolete TV sets indicated that precious metals such as gold, silver, and palladium, and common metals such as iron, aluminum, zinc, and tin will increase due largely to the higher substance concentrations in FPD TV sets. Other common metals such as copper and nickel and toxic metals such as lead will have a fluctuating trend, and other toxic
metals other than lead and plastics will also increase.

These results could help inform waste management and recycling strategies and relevant decision makers (e.g., governmental agencies, manufactures, and recyclers) for the TV sets sector in China. First, the growing generation of TV sets provides huge potentials of urban mining and resource recovery. For example, the large amount of valuable substances such as gold, silver, iron, and aluminum contained in the obsolete TV sets could be recovered through reasonable recycling efforts, which could help relieve resource and environment pressures. Second, the increasing amount of toxic metals (e.g., mercury, barium, and antimony) in obsolete TV sets should be paid special attention and properly treated to protect the environment security and human health.

Current recycling system for obsolete TV sets includes five aspects: recovery, detection and classification, reprocessing, redistribution and waste treatment. In the recovery phase, there are two main recovery channels: formal channel and informal channel, currently with a half-half contribution (Wang, 2013). In order to increase recycling of obsolete TV sets, different stakeholders along the value chain should join efforts. Consumers should extend the lifespan of TV sets as far as possible and should send obsolete TV sets to professional recycling agency (formal channel) instead of discarding or reselling them informally. TV sets manufacturers should have the green production concept to decrease the amount of waste that can’t be reused and follow
the concept of EPR (Extended Product Responsibility), such as taking the obsolete TV sets of their own brands respectively (Gu et al., 2017). From the regulation point of view, proper subsidy policies should be introduced to encourage customers and manufacturers to join the formal recycling network of WEEE.

The dynamic material flow analysis model we developed in this article for obsolete TV sets can also be used for other types of WEEE which show an increasing trend and contain large number of valuable resource, such as computers and mobile phones. It should be noted that the simulated amounts of metals and plastic embodied in generated obsolete TV sets in this model are only theoretical potentials. The actual recycling potentials depend on a few other parameters, such as cost, technology options (collection, sorting, and recycling) and efficiency along the chain, and waste logistics system and its optimization. These factors deserve further analysis in the future.

Acknowledgements

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Department of Chemical Engineering, Biotechnology, and Environmental Technology, University of Southern Denmark, in Spring 2017.

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consequences for health and the environment. Resources, Conservation and Recycling 113, 149-164.


Xu, C., Zhang, W., He, W., Li, G., Huang, J., 2016. The situation of waste mobile phone management in developed countries and development status in China. Waste Management 58, 341-347.


<table>
<thead>
<tr>
<th>Substance</th>
<th>CRT TV set</th>
<th>FPD TV set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Panel</td>
<td>Funnel</td>
</tr>
<tr>
<td><strong>Precious metal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Silver</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Palladium</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Copper</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Iron</td>
<td>0.11%</td>
<td>0.08%</td>
</tr>
<tr>
<td><strong>Common metal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.10%</td>
<td>1.80%</td>
</tr>
<tr>
<td>Copper</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Iron</td>
<td>0.11%</td>
<td>0.08%</td>
</tr>
<tr>
<td><strong>Toxic metal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.01%</td>
<td>21.50%</td>
</tr>
<tr>
<td>Mercury</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Barium</td>
<td>7.90%</td>
<td>0.32%</td>
</tr>
<tr>
<td>Antimony</td>
<td>0.26%</td>
<td>0.15%</td>
</tr>
<tr>
<td><strong>Plastic material</strong></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 1.** Substance concentrations in different types of TV sets
### Table 2. Range of parameters used in our model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average lifespan</td>
<td>8-16 y</td>
<td>The value was changed with estimated method and time</td>
</tr>
<tr>
<td>Weight</td>
<td>10-50 kg</td>
<td>Model, manufacturer, technology, and material choice could all affect the weight of TV sets</td>
</tr>
<tr>
<td>Gold</td>
<td>0.005%-0.016%</td>
<td>Substance concentration could change a lot as technology changes in the future, and the value is different in different types TV sets.</td>
</tr>
<tr>
<td>Silver</td>
<td>0.012%-0.0189%</td>
<td></td>
</tr>
<tr>
<td>Palladium</td>
<td>0.002%-0.012%</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>3%-7.2%</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>3.59%-5.11%</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>2%-14.172%</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>0.91%-2.01%</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>1.8%-2.76%</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>0.032%-0.85%</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.067%-22.91%</td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>0.0002%-0.035%</td>
<td></td>
</tr>
<tr>
<td>Barium</td>
<td>0.0315%-8.46%</td>
<td></td>
</tr>
<tr>
<td>Antimony</td>
<td>0.0094%-0.73%</td>
<td></td>
</tr>
<tr>
<td>Plastic</td>
<td>20.6%-27.3%</td>
<td>The possibility of market share change of FPD and CRT TV set is quite low, but new type of TV sets could be introduced into market with development of technology</td>
</tr>
<tr>
<td>Market share</td>
<td>N.A.</td>
<td></td>
</tr>
</tbody>
</table>
A dynamic, bottom-up, and stock-driven material flow analysis model was developed.

Metals and plastics in obsolete TV sets in China from 1992 to 2040 were analyzed.

Over 142 million units of obsolete TV sets will be discarded by 2040.

Most common and precious materials embodied in obsolete TV sets tend to increase.

Lead will be gradually phased out as FPD TV sets replace CRT TV sets.