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An evaluation of the potential yield of indium recycled from end-of-life LCDs: A case study in China

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ABSTRACT

With the advances in electronics and information technology, China has gradually become the largest consumer of household appliances (HAs). Increasingly, end-of-life (EOL) HAs are generated in China. EOL recycling is a promising strategy to reduce dependence on virgin production, and indium is one of the recycled substances. The potential yield of indium recycling has not been systematically evaluated in China thus far. This paper estimates the potential yield of recycled indium from waste liquid crystal displays (LCDs) in China during the period from 2015 to 2030. The quantities of indium that will be used to produce LCDs are also predicted. The estimates focus on the following three key LCD waste sources: LCD TVs, desktop computers and portable computers. The results show that the demand for indium will be increasing in the near future. It is expected that 350 tonnes of indium will be needed to produce LCDs in China in 2035. The indium recycled from EOL LCDs, however, is much less than the demand and only accounts for approximately 48% of the indium demand. The sustainable index of indium is always less than 0.5. Therefore, future indium recycling efforts should focus on the development of recycling technology and the improvement of the relevant policy.

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1. Introduction

Indium, a scattered element, is rare in the Earth's crust. Indium has no ore of its own and is generally found in low concentrations in some sulphide ores of zinc, copper and lead, from which it is extracted as a by-product (Gupta et al., 2007; U.S. Geography Survey, 2014). The most important end use of indium in recent years has been to manufacture indium–tin oxide (ITO) thin films, an optoelectronic material with the characteristics of transparency to visible light, electric conduction and thermal reflection. These ITO thin films are composed of 90% In2O3 and 10% SnO2 (Virolainen et al., 2011). Currently, ITO thin films are widely used in designing LCDs, plasma displays and solar-energy cells, consuming approximately 70% of the global indium production (Park, 2011; Li et al., 2011).

In China, with advances in electronic information technology, LCDs have gradually replaced cathode ray tube (CRT) displays in the production of televisions and computers. In 2014, 141.29 million colour TV sets were produced, among which LCD TVs accounted for over 98% (Ministry of Industry and information technology of China, 2014). In the same year, 351 million computers including, 227 million laptops, were produced (Ministry of Industry and information technology of China, 2014). With the extensive use of LCDs, the demand for indium will be increasing. According to the prediction of this paper, the demand for indium for producing household appliances (HAs) with LCDs such as TVs and computers will be over 300 tonnes every year.

China ranks first in the world in terms of its reserves of indium. In 2012, the proven reserves of indium totalled 8000 tonnes in China (ASKCI), accounting for approximately 62% of the total global reserves. The annual production of primary indium in China accounts for over 50% of the global production (Minerals Yearbook Indium USGS, 2012). Indium will be sustainable for only 30 years if it is mined at the present scale (more than 400 tonnes per year) (U.S. Geography Survey, 2014).

Currently, the demand for indium is increasing and the exploitation of primary indium is limited. It is difficult to meet the demand by extracting primary indium. It is crucial to recycle indium from the EOL LCDs for the purpose of maintaining the sustainability of indium. Although indium recycling has not yet been industrialized in China, a large number of studies have proven the feasibility of recycling indium from waste LCDs (He et al., 2014; Li et al., 2009; Kang et al., 2011). In these experiments, the purity of indium recycled from waste LCDs can reach approximately 99% (Kang et al., 2011). As a result of the wide use of

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LCDs, the quantity of EOL LCDs will increase each year. Recycling can potentially reduce the dependence on primary indium production while altering the geographic distribution of the indium supply. (Places where there is no indium mine can also provide indium through indium recycling.)

Many scholars have studied the sustainable utilization of resources. For different resources, the suggestion of promoting the sustainable utilization of resources and advices that improve the efficiency of relevant policy are put forward. Jing Yu and Shuzhen Yao discussed a quantitative integrated evaluation of the sustainable development of mineral resources in a mining city (Yu et al., 2005). Frank Figge, Tobias Hahna and Ralf Barkemeyer argued on the feasibility and methods of assessing sustainable resource use (Figge et al., 2014). Resource and Energy Economics published an editorial to discuss the technologies, preferences, and policies for the sustainable use of natural resources (Resource and Energy Economics, 2011). The effects of the recoveries of many metals such as zinc (Yan et al., 2013) and aluminium (Mathieux and Brissaud, 2010) have been analysed by some scholars. In addition, Jelle H. Rademaker and Rene Kleijn evaluated the potential yield of NdFeB recycling from permanent magnets and critically analysed the strategy with respect to rare earth elements (Rademaker et al., 2013). Different from the studies described above, their study paid attention to the rare earth elements in terms analysing the utilization of resources on a more microscopic scale. Actually, it is difficult to find research evaluating the potential yield of indium recycling from EOL LCDs. The sustainability of indium is also seldom discussed. Therefore, in this paper, LCD TVs and computers (desktop and portable) are chosen as the targets. The potential yield of indium recycled from waste LCDs in China and the quantity of indium that will be used to produce LCDs from 2015 to 2035 are estimated. Using these forecast data, the sustainable utilization of indium resources in China has been discussed. This study provides a theoretical basis and some data in support of the sustainable utilization of indium resources in China.

2. Methodology

2.1. The calculation process of the potential yield of indium in EOL LCDs

To arrive at the potential yield of indium recycled from EOL LCDs, first the quantity of EOL LCDs and then the potential yield of indium recycled from EOL LCDs were estimated. For the quantity of EOL LCDs, the sale of a LCD is taken as the starting point. The sale and obsolete amounts of LCDs in the future can be estimated by iterations using the statistical data (the number of HAs per household and the sale of HAs). We will introduce the estimation program in detail in Section 2.3. In the second step, the quantity of indium per unit is calculated using the average screen size of HAs and the indium content of LCD films measured by previous research. The lifetime, the average screen size and the waste flow of HAs were investigated by questionnaire. When the potential yield and the demand of the indium are predicted, the sustainable utilization of indium will be discussed.

We did not take mobile phones into account although the number of waste mobile phones is large. Actually, the indium content in each phone is much less than in these three HAs discussed above, and it is currently difficult to recover mobile phone screens in China. Therefore, mobile phones were not taken into account in this paper.

2.2. The survey questionnaire

The frequency of use of various HAs is different. In addition, the HAs may be replaced due to different reasons such as an improved family financial situation or a change in social trends. These reasons lead to the uncertainty in the lifetime of HAs. Therefore, online survey questionnaires were administered. 630 households were selected randomly from all over the country (see Table 1) between Jan. 10, 2015 and Jan. 15, 2015, and 525 valid questionnaires were received. The survey contained questions on basic socioeconomic information as well as three other parts. The socioeconomic information included questions regarding age, sex, city and number of families. The first of the three additional survey parts uncovered the number of HAs; the second part aimed to investigate the intended lifetime of HAs; and the last part surveyed the waste flow of the HAs (see Table 2). The meaning of the "intended lifetime" simply known as the "residential time" was defined by Murakami et al. (2010). Residential time is defined as the duration of existence of the goods in question, such as materials or substances in our society, regardless of whether the goods still function. The waste flow of these HAs is investigated in the questionnaire. As a result, the ratio of EOL HAs that can be recycled will be gained. The results of the survey supported the assumption. The detailed result of survey is available in the Supporting information.

2.3. Estimation model of the amounts of EOL HAs

In the previous studies, scholars estimated the amounts of EOL HAs using different methods. Yu et al. (2010a,b) estimated the generation of retired mobile phones in China with a material flow analysis method. Bo Li made a comparative study on the methodology based on the estimation results of retired mobile phones using the market supply A method, the consumption and use approach and the sales and new method (Li et al., 2015). Actually, waste amounts of other HAs such as televisions, refrigerators, washing machines and computers in different countries has also been estimated by many scholars (Rahmani et al., 2014; Habuer et al., 2014; Wang et al.,2013). Yan Yang and Eric Williams forecast the sale and generation of obsolete computers in the U.S. based on the logistic model (Yang and Williams, 2009). We modified their estimation model in this paper, and the details will follow.

2.3.1. Calculation of the annual quantity of HAs owned by households

The growth of product consumption can be normally divided into the following four phases: primary introduction, rapid growth, saturation and final decline in some cases. The growth curve of the average number of home appliances per household has an "S" shape if the phase of decline is not considered (Liu et al., 2006). The logistic model has its roots in ecology in modelling population growth (Yu et al., 2002). It can be defined by the logistic function in Eq. (1).

$$\overline{P_t} = \overline{P}_{\max}/(1 - b_0 \cdot \exp[-b_1 \cdot (t - t_0)]) \quad (1)$$

$$P_t = \overline{P_t} \cdot H_t \quad (2)$$

$$H_t = N_t/S \quad (3)$$

$$N_t = N_{t-1} \cdot (1 + d) \quad (4)$$

where $\overline{P_t}$ is the average number of HAs per household at the end of the t-th year, $\overline{P}_{\max}$ is the maximum of the average number of HAs

Table 1
The geographic distribution of the surveyed households.

Region	Number	Proportion (%)
The eastern region	255	48.6
The middle region	160	30.5
The western region	110	20.9

Table 2
Questionnaire.

Basic information			
age	sex	city	number of families
Part 1. Number of HAs			
1. How many LCD TVs do you have?	☐ 1 ☐ 2 ☐ 3 ☐ 4		
2. How many LCD desktops computers do you have?	☐ 1 ☐ 2 ☐ 3 ☐ 4		
3. How many portable computers do you have?	☐ 1 ☐ 2 ☐ 3 ☐ 4		
Part 2. The intended lifetime and screen size of HAs			
4.How long do you expect your LCD TV to be used?	☐ 5 ☐ 7 ☐ 8 ☐ 9☐ 10 ☐ 11		
5.How long do you expect your LCD desktop computers to be used?	☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8		
6.How long do you expect your portable computers to be used?	☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8		
7.What is the screen size (inches) of your LCD TV?	☐ 21 ☐ 25 ☐ 29 ☐ 32 ☐ 32-40 ☐ 40-50 ☐ 50-60 ☐ more than 60		
8.What is the screen size (inches) of your LCD desktop?	☐ less than 19 ☐ 19-22 ☐ 22-26 ☐ more than 26		
9.What is the screen size (inches) of your portable computers?	☐ less than 12 ☐ 13 ☐ 14 ☐ 15 ☐ more than 15		
Part 3. How to deal with			
10.How to deal with the waste LCD TVs?	☐ sellers ☐ formal recycling sectors☐ peddlers ☐ the secondary market ☐ idle at home ☐ discard		
11.How to deal with the waste LCD desktop computers?	☐ Sellers ☐ formal recycling sectors☐ peddlers ☐ the secondary market ☐ idle at home ☐ discard		
12. How to deal with the waste portable computers?	☐ Sellers ☐ formal recycling sectors☐ peddlers ☐ the secondary market ☐ idle at home ☐ discard		

per household, b_0, b_1 are the parameters, H_t is the number of households, P_t is the total number of HAs owned by households at the end of the t-th year, N_t is the population, S is the family size, and d is the natural growth rate of the population.

The annual quantity of HAs owned by households from 2003 to 2012 is researched on the official website of the National Bureau of Statistics of China (National Bureau of Statistics of China). We assume that the natural growth rate of the population for the years from 2015 to 2035 will be 0.49%, which is the growth rate reported in the China Statistical Yearbook for the years 2009 to 2013. The National Bureau of Statistics of the People's Republic of China claimed that the size of an urban household was approximately 2.9 people per household, and that of rural families declined from 4.0 to 3.9 people per household from 2007 to 2012. Family sizes were reported to be stable. According to the census in 2010, the average family size for the entire country was 3.10 people per household (National Bureau of Statistics of China). We set the family size at 3.10 people per household so that the number of households could be obtained.

As for the maximum of the average number of HAs per household, it is difficult to give an accurate estimate because there are complicated factors exerting influence on the use of HAs. We therefore set an upper and a lower bound for this statistic. In addition, the specific contents of the assumptions are given in the section captioned "Key Assumptions".

2.3.2. Accumulated obsolete ratio

The Weibull distribution was discovered by Waloddi Weibull in 1936. Weibull Distribution (WD) can preferably reflect the fatigue strength and fatigue life of mechanical products and their parts under random loads (Ali et al., 2015). WD has often been used in the characterization of probabilistic behaviours of a large number of real life phenomena. This distribution is especially used as a failure model to analyse the reliability and maintainability of different system types (Nasr et al., 2013). In this paper, we assume that the intended lifetime of a HA is a random variable that is independently identically distributed. Therefore, the intended lifetime is the Weibull distribution. The distribution function is as follows:

$$W(x) = 1 - \exp\left[-c_0 \cdot x^{c_1}\right] \tag{5}$$

$$\overline{X} = \sum x \cdot [W(x) - W(x-1)] \tag{6}$$

$$f(x) = W(x) - W(x-1) \tag{7}$$

where $W(x)$ is the accumulated waste ratio when the HA has been used for x years, c_0, c_1 are the parameters, $\overline{X}$ is the average lifetime of a HA and $f(x)$ is the scrap rate when the HA has been used for x years.

In this paper, the intended lifetimes of LCD TVs and computers (desktop and portable) were investigated, and then, the data obtained was fitted into the Weibull distribution formula based on the maximum likelihood estimation. As a result, we obtained the probability distribution functions of these three HAs, and the probability distributions are presented in Fig. 1.

The intended lifetimes of the HAs are as follows: LCD TV, 6–11 years; desktop computer, 3–8 years; and portable computer, 2–7 years.

2.3.3. Amount of annual waste

The amount of annual waste here is determined by the annual sales and the waste probability of the HAs of the corresponding year. The sale is defined by function (7). The actual waste amount could not be obtained alone, and so, it was calculated using Eqs. (8) and (9).

$$O_t = \sum S_{t-x} \cdot f(x) \tag{8}$$

$$S_t = P_t - P_{t-1} + O_t \tag{9}$$

where O_t is the waste amount in the t-th year, S_{t-x} is the quantity sold in the $(t-x)$-th year ($x \geqslant 1$), $f(x)$ is the waste rate when the HA has been used for x years and P_t is the amounts of HAs owned by the total households at the end of the t-th year. The annual sales data are from the China Statistical Yearbook of electronic information industry (China Statistical Yearbook of electronic information industry).

The values of the parameters mentioned above are shown in Table 3

3. Key assumptions

Due to the lack of relevant data, the estimations and predictions of this paper are based on the following assumptions:

3.1. Average screen size

For the monitors of different appliances whose screen sizes are different, the assumptions are based on the results of the online survey. The results showed that the most widely used LCD TV screen size is 30–50 in., that of desktop computers is 19 in., and that of laptops is 14 in. Therefore, 40, 19 and 14 in. were set as the average screen sizes of LCD TVs, desktop computers and portable computers, respectively.

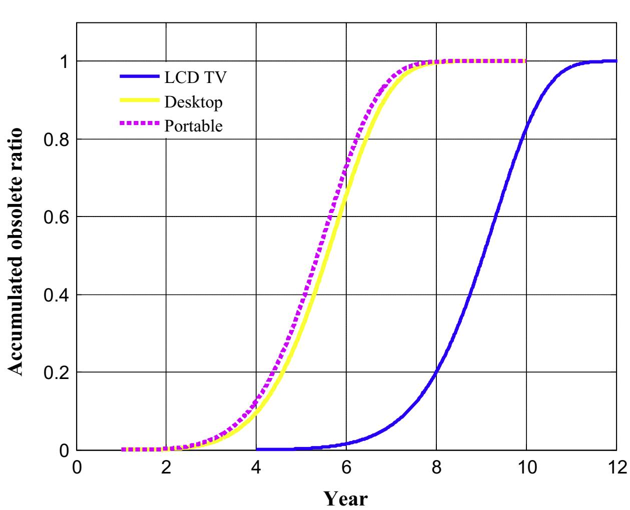

Fig. 1. Probability distributions of lifetimes of HAs.

Table 3
The values of the parameters.

	Bound	t_0	b_0	b_1	c_0	c_1	S	d (%)
LCD TV	Upper	2010	14.22	0.76	9.41	5.01	3.10	0.49
	Lower		11.93	0.75				
Desktop	Upper	2010	16.64	0.85	5.94	4.67		
	Lower		13.25	0.84				
Portable	Upper	2010	23.30	0.85	5.72	4.78		
	Lower		18.60	0.85				

Notes: The logistic model is solved by SPSS, and the fitting function is $\overline{P_t} = \overline{P}_{\max} \Big/ (1 - b_0 \cdot b_1^{(t-t_0)})$.

3.2. The maximum number of appliances per household

To obtain more accurate results, the upper bound and lower bound of the maximum number of household appliances per household were set. According to the assumptions of the number of PCs per capita in the U.S. as set by Yang and Williams, the maximum number of PCs per capita is related to the age structure and social workforce. In detail, the upper bound was set by assuming that every employed person has their own computer at work and that every person aged from 10 to 84 has their own personal computer for entertainment or other personal needs. Conversely, the lower bound was set by assuming that only information workers have a computer. In the end, they estimated that the upper bound should be equal to 1.3 units per capita, and the lower bound should be equal to 1.0 unit per capita (Yu et al., 2010a,b). In addition, in a study about computer waste generation in India conducted, 0.0336 computers per capita was set as the total lower bound for the carrying capacity, and they assumed that the upper bound of the carrying capacity was 1.027 computers per capita (Dwivedy and Mittal, 2010).

Different from that of Yang and Williams, the quantity of HAs per household rather than per capita is chosen to be estimated in this paper. Apparently, it is more reasonable to do this because HAs are used by every family member in China. The number of these three HAs (LCD TVs, portable computers and desktop computers) per household was investigated by the questionnaire, and the assumptions below were made based on the results of the questionnaire.

Based on the investigation, 10% of the households have 2 LCD TVs, and more than 60% of households have one. Considering the fact that a TV is a necessity for every household, in this paper, the lower bound of the maximum of the number of HAs per household was set at a unit of 1.0. In the near future, we look forward to seeing that 20% of Chinese households will have 2 LCD TVs, and 80% will have at least one. It is very popular to buy LCD TVs in China, and so, it is reasonable to assume that the upper bound of the maximum is 1.2 units per household.

The computers in this study are categorized as desktop and portable computers. With the development of electronic information technology and the popularization of e-commerce, daily life, academic life and work are increasingly becoming inseparable from the computer. For desktop computers, the results showed that almost 40% of the surveyed households have a desktop computer, and approximately 18% of the surveyed households have two. Compared with the situation in developed countries, the average number of desktop PCs in China is bound to increase, and so, the lower bound of the maximum number is assumed to be 0.8 units per household. However, considering the situation of the entire country, 1.0 unit was set as the upper bound of the maximum number for each household.

For portable computers, according to the results of the survey, more than 60% of the surveyed households have a portable computer, and close to 28% of households have two. Therefore, we assumed 1.2 units as the lower bound of the maximum number of portable computer per household. However, taking into account the convenience of the laptop, teachers, students, IT professionals and even ordinary persons cannot work or recreate without a portable computer. Therefore, we assumed that the upper bound of the maximum number of portable computers is 1.5 units per household.

After selecting the maximum number of these three home appliances per household, the data were fitted into the logistic curve model and then the functions of the logistic curves were obtained. We can therefore predict the numbers of these three household appliances per household in the future. The predicted logistic curves are shown in Fig. 2.

In Fig. 2, the average number of LCD TVs per household will be close to the maximum in 2030, while those of desktop and portable computers will be close to the maximum in 2050 and 2060, respectively. In the next 20 years, a large quantity of LCDs will be needed to produce computers and TVs.

3.3. The content of indium per LCD

Many scholars have detected the indium content in LCDs. Hiroshi hasegawaa, used ICP–OES to analyse LCD-waste samples and found that the indium content is within the range of 380–410 mg/kg liquid crystal glass (Hasegawa et al., 2013). According to the results obtained by Jiaxu Yang, Teodora Retegan and Christian Ekberg, a 17 in. LCD glass is approximately 3.2 kg/m^2, and the indium content is 0.25 g In/kg glass (Yang et al., 2013). In this study, under the assumption that indium is evenly distributed in the ITO layer, with the above data, the indium contents of the three household appliances were set as follows: the indium content in desktop computers is 0.083 g per unit, that of portable computers is 0.072 g per unit, and that of LCD TVs is and 0.354 g per unit.

3.4. The recovery rate of EOL LCDs

The recovery rate here is defined by the percentage of the LCDs that flow to sellers and the formal recycling sectors. In this paper, we are convinced that only sellers and the formal recycling sectors can recycle indium from EOL LCDs, and we assume that the indium in the LCD was completely extracted. Therefore, according to the questionnaire the following assumptions were set: the recovery rate of LCD TVs is 54.6% (30.4% of them flow to sellers and 24.2% flow to the formal recycling sectors), the recovery rate of portable computers is 54.1% (33.9% of them flow to sellers and 20.2% flow to the formal recycling sectors), and the recovery rate of desktops is 42.9% (20.4% of them flow to sellers and 22.5% flow to the formal recycling sectors). The detailed waste flows of these three household appliances are shown in Fig. 3.

In Fig. 3, the main flow of waste HAs is to sellers, formal recycling sectors, peddlers and the secondary market. Apparently, more households choose to leave the computers idle at home than discard them considering the safety information.

The key assumptions in this paper are shown in Table 4.

4. Sustainable index

To show the percentage of the potential yield of indium recycled from EOL LCDs and account for the indium demand for producing LCDs, the sustainable index is defined by function (8) as follows:

$$\text{Sustainable Index} = \frac{\text{indium recycling from EOL LCDs}}{\text{indium demand for LCD producing}} \tag{10}$$

The sustainable index is a constant that is always bigger than zero. When it is less than one, it means the indium recycled from EOL LCDs is less than the demand for LCD production, and the indium recycled from EOL LCDs cannot be sustainable. When the index is equal to or greater than one, it means the indium recycled from EOL LCDs is equal to or more than the indium demand for LCD production, and the indium recycled from EOL LCDs can be sustainable.

5. Results and discussion

5.1. The predicted amounts for indium demand

With advances in electronic information technology, LCDs are widely used in HAs. According to the prediction of the quantity of these three HAs per household, the demand for computers (portable and desktop) will increase in the coming years, and the demand for LCD TVs will hold steady at a high level. As a result, the demand for indium will be tremendous. The demand for indium for producing LCD TVs will be steady at 150 tonnes every year. The demand for indium for producing portable computers

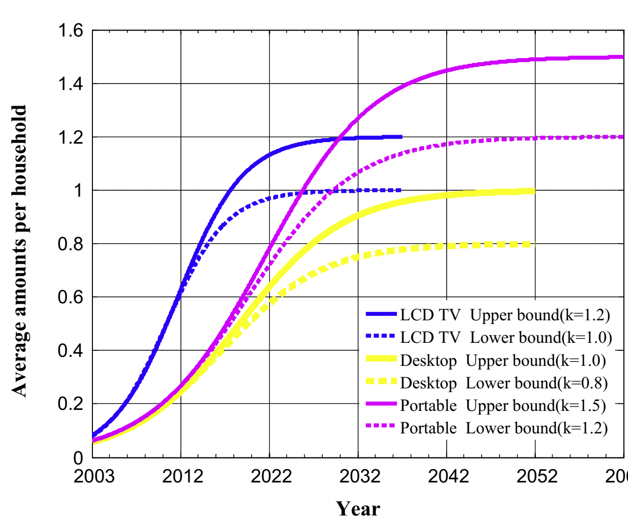

Fig. 2. The average number of the three house appliances per household.

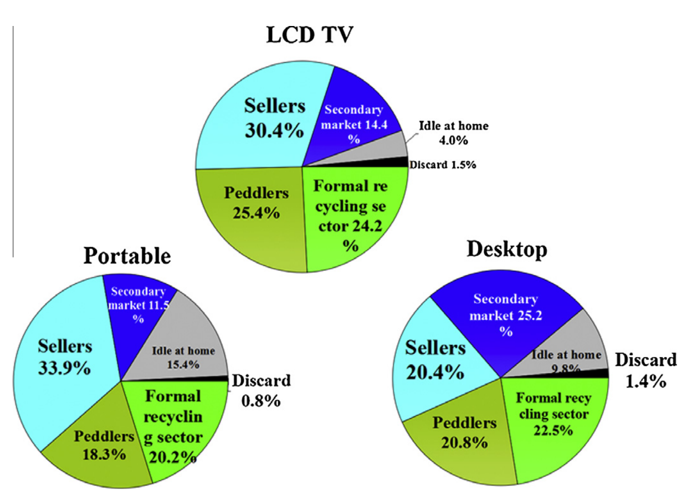

Fig. 3. The waste flows of the three home appliances.

Table 4
The key assumptions in this paper.

Assumption		PC		LCD TV
		Desktop	Portable	
Screen size (inch)		19	14	40
Recovery rate (%)		42.9	54.0	54.6
Average number per household	Upper bound	1.0	1.5	1.2
	Lower bound	0.8	1.2	1.0
Indium content (g)		0.083	0.072	0.354

will keep increasing rapidly from 2020. Simultaneously, the total demand of indium will be up to approximately 350 tonnes in 2035 based on the upper bound assumption. The demand for indium based on the upper bound can be found in Fig. 4.

5.2. The potential yield of indium recycled from the EOL LCDs

The potential yield of indium recycled from EOL LCDs and the sustainable index of indium from 2013 to 2035 based on the upper and lower bounds are presented in Figs. 5 and 6, respectively. The increasing tendencies of indium recycled from EOL LCDs based on these two bounds are similar. The potential yield of indium will be increasing rapidly before 2020, and then the growth will slow down beginning in 2021. Until 2030, the growth will be close to zero. This means the yield of indium recycling will be low if the present conditions are not changed. Obviously, the indium recycled from EOL LCD TVs is almost more than the quantity of indium obtained from recycling the other two HAs (desktop and portable computers). Therefore, more efforts should be made to recycle EOL LCD TVs.

5.3. The sustainability of indium

Next, we pay attention to the sustainable index of the indium based on the upper bound. According to Fig. 5, the sustainable index is below 0.3 before 2019. From 2013 to 2019 the growth of the index is fast but will slow down beginning in 2020. Until 2035, the index will still be less than 0.5. Unfortunately, it seems that the situation will remain unchanged in the future.

The main reason why the sustainable index is so low during the 2013–2019 period is that the demand for indium is huge as a result of the popular application of LCDs. Meanwhile, the indium recycling is very low because the number of EOL LCDs is few. Actually, LCDs began to be popular in China beginning around 2005. As a result, there are few LCDs that can be recovered during the 2013–2019 period.

Another reason for the low sustainable index is the low recovery rate of waste LCDs. According to the investigation on waste LCD flows, it is clear that the current recycling system for EOL HAs has not been fully established in China, and at the same time, the management of formal recovery sectors is not standardized. Therefore, when families are confronted with electronic waste, they have no idea on how to deal with it appropriately. What they do is leave these EOL appliances at home or sell them to peddlers, which greatly slows down the recovery efficiency. Actually, research has shown that e-waste bans, the convenience of recycling facilities and services and economic benefits are determinants of people's willingness and behaviour in e-waste recycling (Milovantseva and Saphores, 2013; Wang et al., 2011). Conversely, the market mechanism of HA recycling in China is not yet perfect, and the profits of the recycling business are too low to attract investment, which slows down the development of the appliance recycling industry. For example, the profit from a cell phone is much more than that from the recycling (Geyer and Blass, 2010). Lastly, the technology of dismantling and purification has

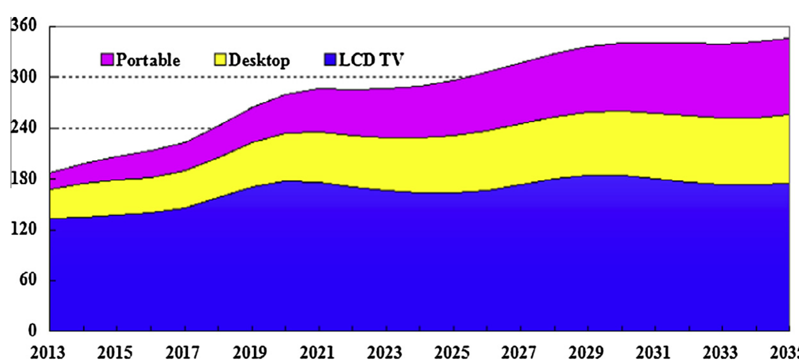

Fig. 4. The indium demand for producing LCDs from 2013 to 2035 based on the upper bound.

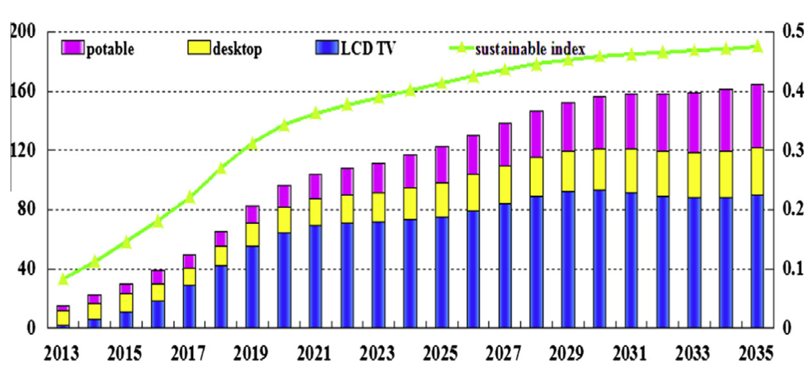

Fig. 5. The potential yield of indium and sustainable index based on the upper bound.

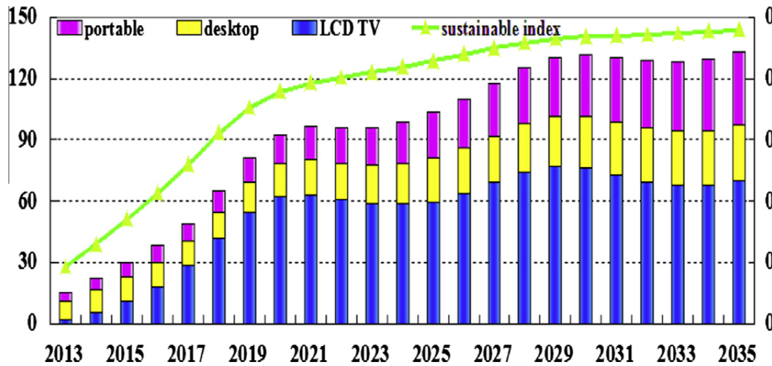

Fig. 6. The potential yield of indium and sustainable index based on the lower bound.

not yet matured. All of these problems mentioned above have severely restricted the industrial development of HA recycling, and only when these issues are resolved can the EOL HAs be effectively recovered. Eventually, the precious resources (such as indium resources) in these HAs can be recycled with a high efficiency. In recent years, relevant laws and regulations of e-waste have been practiced in China (Yin et al., 2014), and technological progress and innovation of refined metal resources are encouraged by the government. Thus, initial success has been achieved in solving these problems. In addition, the experience of other countries is very helpful to China (Shekdar, 2009). Especially Japan (Oguchi et al., 2012).

To make indium resources sustainable, besides recycling, there are three possible methods including the following: reducing the use of indium, finding some elements with the same properties to substitute for indium and improving the efficiency of indium. These three ways can be useful in some applications of indium resources. Obviously, advancement in technology is essential to make these a reality.

In addition, if waste LCD monitors are not recovered well, the toxic element arsenic in the LCD monitors will pose a huge threat to the environment and the health of humans (Kiddee et al., 2013).

6. Conclusion

The potential yield of indium recycled from EOL LCDs is obtained based on the calculated model and assumptions in this paper. The demand for indium from 2013 to 2035 is also predicted. It is evident that the demand is much higher than the available quantity obtained from recycling EOL LCDs. Furthermore, the sustainable index is always less than 0.5, so it is critical to find a feasible approach for the sustainable use of indium. More technological advances are needed for increasing the efficiency of indium or an improvement in the recycling policy is needed to support these work.

In this paper, the prediction of the potential yield of indium recycling does not cover all applications of indium resources. The LCD monitor is selected for the prediction of the potential yield of indium because the majority of the indium consumed is used in the production of LCD monitors, and LCD monitors are easy to recover.

Furthermore, the results in this paper are based on a series of assumptions and the results of previous studies. As a result, the actual quantity of indium recycled from EOL LCDs may be less (about 2%) than the value in theory. We conducted a survey to obtain enough relevant data. It is obvious that the results of the survey are not accurate to reflect the actual situation. To obtain more accurate forecasts and estimations, assumptions such as the lifetime of home applications, indium contents in the LCDs and recovery rate of the EOL LCDs need to be improved in the future, which will require more accurate statistical research. In addition, this paper estimates that the potential yield of indium from recycling is limited to LCDs. Estimations in the future can be extended to cover all other applications of indium.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2015.07.047.

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