Journal of Cleaner Production 127 (2016) 331–338

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Waste electrical and electronic equipment (WEEE) recycling for a sustainable resource supply in the electronics industry in China

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ARTICLE INFO

Article history:
Received 5 August 2015
Received in revised form
27 February 2016
Accepted 9 April 2016
Available online 20 April 2016

Keywords:
WEEE
Recycling
Estimating
Sustainable resource supply
Electronics industry

ABSTRACT

High consumption of electrical and electronic equipment (EEE) is accompanied with a high yield of waste electrical and electronic equipment (WEEE). Meanwhile, because the different types of resources have their own unique properties, the current content of each type will remain limited in a range of fluctuations. Therefore, WEEE recycling is an obvious choice to meet the resource demands of the electronics industry. However, there are uncertainties as to whether a sustainable resource supply of the electronics industry can be achieved using secondary resources recycled from WEEE. A dynamic sustainable supply model was used to estimate the resource sustainability supply index (*SSI*) and the primary resource accumulated consumption (*PRAC*) from 2010 to 2050. Four scenarios, which changed one of the key assumptions of the model, were used to assess the impact on the *SSI* and *PRAC*. These four scenarios are lifespan shortening scenario, high-speed formal recycling growth scenario, high formal recycling peak scenario, and the resource reduction scenario, respectively. Subsequently, a combined policy scenario based on their advantages was built and demonstrated to be a feasible method to achieve a sustainable resource supply using recycled resources. To achieve this scenario, the support of government policy is suggested. However, the policy of the funding system in China can only be used as an assistant policy because it is unsustainable and cannot fundamentally squeeze backyard recyclers out of the market. The Extended Producer Responsibility system can be employed to improve the formal waste recycle network system in the long run, and in this way, a sustainable resources supply can be achieved by 2037 in Beijing, China.

1. Introduction

Electrical and electronic equipment (EEE), such as televisions (TV), computers (PC), washing machines (WM), air conditioners (AC), and refrigerators (RE), are essential for our daily life and are widely used in homes and offices. As a result, the electronics industry has become the world's largest and fastest growing manufacturing industry (Wath et al., 2010). The development of this industry is largely based on the increasing availability of physical resources (Chancerel et al., 2009; Yin et al., 2014). In the past decades, the diverse market needs have led to a rapid growth of EEE categories (Qu et al., 2013), resulting in a shortened lifecycle and a rapid replacement of obsolete EEE (Umair et al., 2015; Xianlai et al., 2013).

Increasing consumption of EEE products naturally leads to a high yield of waste EEE (WEEE). As a result, WEEE constituted 8% of all municipal waste in 2004 (Widmer et al., 2005), further increasing by 3–5% per annum (Afroz et al., 2013; Rahimifard et al., 2009). While the annual growth rate of WEEE generation in China is 13–15%, which is much higher than the world average level (He et al., 2008). Using PC as an example, it is estimated that the generation of obsolete PCs in developing countries will exceed that of developed countries between 2016 and 2018 and will double that of developed countries by 2030 (Yu et al., 2010).

Recycling has long been known to be an environmentally-friendly strategy and an appropriate way to manage WEEE streams (Zhang et al., 2011). The diverse types of resources recycled from WEEE can potentially replace an equivalent quantity of materials that would otherwise need to be produced from primary resources (Menikpura et al., 2014). Moreover, with the development of eco-design, extended/individual producer responsibility system and sustainable supply chain management, resources and components contained in WEEE are likely to be used in the

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http://dx.doi.org/10.1016/j.jclepro.2016.04.041

electronics industry, forming a closed-loop system of resource supply (Garg et al., 2015; Georgiadis and Besiou, 2008; Lifset and Lindhqvist, 2008; Mayers et al., 2011; Mota et al., 2015). Therefore it is possible to achieve self-sufficiency of resources in the electronics industry using secondary-resources recycled from WEEE. And WEEE recycling can effectively provide a solution to the new norm of resource constraint faced in China.

Meanwhile, because the different types of resources such as metal, plastic and glass have their own unique properties, the current content of each type of them will remain limited in a range of fluctuations to meet the defined performance requirements of electronic products, except for the breakthrough of electronic technology, regulations on the compulsory reduction of toxic components, or the reduction of high-value precious metal due to reduced market demands. For example, the metal content has been and will still be dominantly above 50 wt% of EEEs (Ongondo et al., 2011; Widmer et al., 2005). Therefore, in order to achieve a sustainable resource supply, WEEE recycling is an obvious choice to meet the demands of the electronics industry.

China is the world's largest electronics manufacturing country. The shipment of the five main EEEs (i.e., TV, PC, WM, AC, and RE) produced in China reached 760 million units in 2013 (NBSC, 2014). Meanwhile, China has become the largest dumping site for WEEE (Chi et al., 2011; Song and Li, 2014), with more than 114 million units of obsolete EEE products in 2013 (CMC, 2014). While these figures represent potentials for recycling WEEE in China to utilize resources embedded in WEEE, uncertainties exist in terms of whether a sustainable resource supply of the electronics industry can be achieved using secondary-resources recycled from WEEE. This study uses the five main WEEEs in Beijing, China as a case study and examines the potential of a sustainable resource supply based on recycled materials from WEEE. In particular, we estimate the resource demand of the electronics industry and the secondary-resource supply from WEEE recycling between 2010 and 2050 using a dynamic sustainable supply model.

2. Method and materials

2.1. Data sources

The time-series data of the EEE historical penetration rate in households is shown in the Beijing Statistical Yearbook (BSB, 2014) and is used to estimate sales and obsolete quantity. In particular, PCs and ACs are both used in offices. And the office penetration rate of EEE for the PCs can be derived from the China Statistical Yearbook (NBSC, 2014), whereas that of the ACs is determined from a questionnaire survey, which is details in Supporting Information (SI). The results from surveying 500 residents show that the AC penetration rate in offices is approximately 0.19 units per employee. Data on the number of population and employees are from the Beijing Statistical Yearbook (BSB, 2014). We assume that the long-term changes in both are consistent with the overall trend of China's demography derived from the UN Population database (United Nations, 2012). The material flow of obsolete EEE is also obtained from the survey. The weights of WEEE are derived by averaging WEEE weights in three most relevant studies (Chung et al., 2011; Liu et al., 2006; Yang et al., 2008) (details in SI).

2.2. EEE sales and obsolete quantity estimation

2.2.1. Logistic model to estimate the penetration rate

Logistic model is widely used to estimate EEE penetration rate (Dwivedy and Mittal, 2010; Wang et al., 2015; Yang and Williams, 2008, 2009). This model assumes that there is an asymptotic value to the penetration rate growth curve which is in an “S” shape. The differential equation is

$$dp/dt = rp(1-p/K) \tag{1}$$

where p represents the penetration rate of EEE, r is the intrinsic growth rate, and K is the asymptotic value. Although in principle K can be identified from the statistical fit of the historical time-series penetration rates, it will not be accurate in the case when the data are still in early stage and has yet to reach the inflection point of the “S” shape (Yang and Williams, 2009).

In this study, a bounding approach is used to determine the lowest and highest possible values of K. Historical penetration rates of TV, RE, AC, and WM from 1980 to 2010 indicate saturation, while there is still great potential for the growth of PC. The upper bound (UB) of K is estimated by assuming that every person aged from 20 to 70, accounting for approximately 80% of the population, has their own personal computers and that every employee has computers at work (Yu et al., 2010). The lower bound (LB) is set by assuming that only 3/4 of the wealthier residents will have computers at home and 30% of the employees in the primary industry, 60% in the secondary industry, and 90% in the tertiary industry will have computers at work. Penetration rates are then estimated using the logistic model.

2.2.2. Weibull distribution to estimate the lifespan

Various definitions of product lifespan are summarized by (Murakami et al., 2010). In this study, lifespan is defined as the possession span, which starts from a product's shipment to the disposal by the first owner. Therefore, the average lifespan of a product in this step does not include any hibernation or reuse period after the product is no longer in-use by the first owner, but before it becomes a WEEE. This treatment is mainly due to the fact that consumers surveyed in this study do not always know how long their EEE devices will be reused after secondary trading.

To estimate the number of obsolete EEE devices, it is essential to know the lifespan distribution. According to a review by (Oguchi et al., 2010), non-parametric approach and parametric one (including normal distribution, weibull distribution et al.) can be used for estimating lifespan distribution. If accurate data are available, the estimated lifespan distribution should not differ by methodologies. However, due to the fluctuation of the survey data, a more accurate model is needed. Weibull distribution is used for the estimation in this study, which is considered as the best available approach (Daniel et al., 2007). In particular, the probability density function is given by

$$f(t;u,v) = \frac{u}{v}\left(\frac{t-t_0}{v}\right)^{v-1} \exp\left[-\left(\frac{t-t_0}{v}\right)^{u}\right], t \geq t_0 \tag{2}$$

where t is the random variable characterized by a location parameter t_0, u is the scale parameter, and v is the shape parameter. In this study, u and v is determined by fitting with the maximum-likelihood method using the data from the survey. And the lifespan distribution of each EEE device $g(i)$ is estimated by solving the above equation.

2.2.3. Stock-based model to estimate the future sales and obsolete quantity

The principle of mass conservation is used to quantify the flow of materials in a system defined by spatial and temporal boundaries (Kim et al., 2013; Rademaker et al., 2013; Zhang et al., 2011). The in-use stock is affected by the counterpoise of the outflow and inflow. When the inflows exceed the outflows, the stock will increase and vice versa. The relationship between stocks and flows is represented by

$$S_t = P_t - P_{t-1} + O_t \tag{3}$$

where P_t is the in-use stock of EEE in the year t. S_t and O_t represent the EEE sales quantity and obsolete quantity, indicating the inflow and the outflow of the system, respectively. Moreover, S_t and O_t are related by the lifespan distribution $g(i)$, which means that the sales quantity in the previous year becomes obsolete in the year t:

$$O_t = \sum_{i=1}^{t} S_i \cdot g(i) \tag{4}$$

Because both S_t and O_t in Beijing are unknown, the equations will continue extending to the previous years when simultaneously solving equations (3) and (4). It is assumed that the beginning is the year when the household penetration rate exceeds 0.001, and the same year is also suitable for office-use.

2.3. Sustainable capability assessment of resource supply

2.3.1. Carnegie Mellon model to estimate recycled WEEE

Not all the obsolete EEE will be recovered and recycled immediately. The Carnegie Mellon method can be used to solve the situation where the re use and storage parameters of obsolete EEEs were included, which in reality would delay their entry into the waste stream (Matthews et al., 1997). The relationship between the obsolete EEEs and recycled WEEE is represented by

$$R_t = \sum_{i=1}^{t} O_i \cdot \eta_i \tag{5}$$

where R_t is the quantity of recycled WEEE in the year t and η_i is the ratio of obsolete EEE generated in the year i and recycled in the year t.

Rich resources are contained in WEEE (Widmer et al., 2005; Yang et al., 2008). Direct landfill disposal of the waste of the five main EEEs basically does not exist in China. Even if WEEEs are discarded by consumers, they will still be recovered by peddlers evidenced by our survey. The WEEE reverse logistics in Beijing is shown in Fig. 1. Approximately 44% of obsolete EEEs become WEEEs and are recycled by dismantling companies in the same year. The other 56% goes into hibernation (one year), reuse or donation (three years) (Liu et al., 2006).

2.3.2. Dynamic sustainable supply model to evaluate sustainability

Two indicators are used to assess the sustainability of resource supply in the electronics industry using recycled resources. First, the sustainability supply index (*SSI*) is defined as the proportion of primary resources used in the electronics industry that can be substituted by secondary resources recycled from WEEE. Second, primary resource accumulated consumption (*PRAC*) is defined as the amount of primary resources which should be used in a period of time to meet the remaining resource requirements of the electronics industry.

A dynamic sustainable supply model is used to measure the two indicators. As shown in Fig. 2, the model is based on the lever principle and extends into the long-term dynamic process for comparing the indicators in different periods. The purpose of the lever is to meet the resource demand of the electronics industry ($F_t^{in} \cdot w_j^{in}$) using the supply of secondary ($F_t^{out} \cdot w_j^{out}$) and primary resources (ΔF), where F_t^{in} and F_t^{out} are the sales quantity of EEE and the recycled WEEE; w_j^{in} and w_j^{out} are the weight of resources contained in EEE and WEEE, respectively; and j is the category of resources. *SSI* in year t can be expressed as:

$$SSI(t) = \frac{F_t^{out} \cdot w_j^{out} \cdot l}{F_t^{in} \cdot w_j^{in}} \tag{6}$$

PRAC can be expressed as:

$$PRAC(t) = \sum_{i=t_o}^{t} (\Delta F_{i,j}) = \sum_{i=t_o}^{t} \left(F_i^{in} \cdot w_j^{in} - F_i^{out} \cdot w_j^{out} \cdot l \right) \tag{7}$$

where t_0 and t are the selected initial and termination year. Because not all of the resources recycled from WEEE can be used in the EEE industry, the torque of the lever, which is l in the two equations, is essential to measure the actual utilization rate. In particular, $l = (1-\alpha)\cdot(1-\beta)$, where α is the proportion of downgraded resources recycled from WEEE and β is the loss ratio in the refining process. More value of *SSI* is more desired with $SSI(t) = 1$(ASD) as the optimal.

In developing countries, especially China, the value of l is crucial because informal backyard recyclers with less advanced technology and equipment still dominate in the recycling market (Chi et al., 2014; Li et al., 2015; Sthiannopkao and Wong, 2013). This means many precious metals are wasted during informal recycling. Also secondary copper recycled by backyard recyclers cannot reach the grade of electrical copper which needs to meet the purity standard of 99.95%. However, copper used in EEE is mainly in the form of coil and wire, which belongs to the category of electrical copper. Therefore, resources recycled by backyard recyclers flow out of the system. In contrast, dismantling companies send waste resources to formal metal smelting facilities so that the recycled resources can achieve the grade of primary resources and can then be used in the electronics industry. Meanwhile, according to the estimation by Wen (1989), China's metal utilization rate reached 98% in the smelting process in 1989. We assume that the loss of resources is

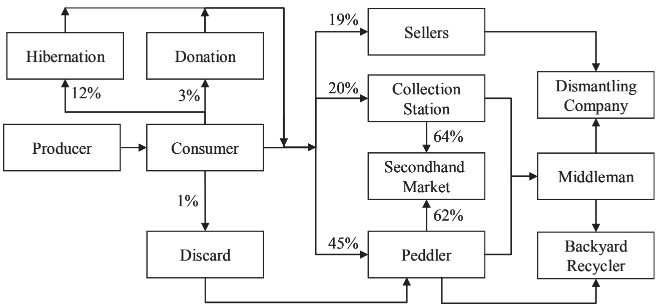


Fig. 1. Material flow of WEEE reverse logistics in Beijing.

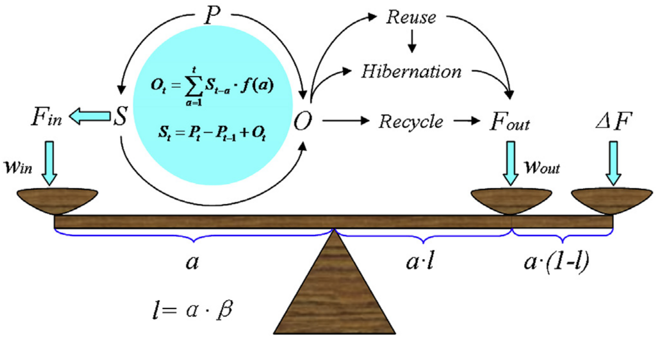


Fig. 2. Dynamic sustainable supply model to measure sustainability.

currently negligible. Thus, the value of l is approximately equal to the proportion of WEEE flow in formal dismantling companies. According to (CNRRA, 2014), WEEE recycled by dismantling companies was approximately 41.5 million units, which only accounts for 36.3% of the quantity of the WEEE recovered 114.3 million units in 2013 (CMC, 2014). Because China's formal recycling industry was just started in 2011, there is still a great potential for development. An annual growth rate of 2% is assumed for the formal recycling ratio with a maximum of 85%, which is the WEEE collection rate in 2019 set by the EU (European Union, 2012).

3. Results

3.1. In-use stocks of EEE in Beijing

The penetration rate of household EEE in Beijing is shown in Fig. 3, whereas that of office-using EEE is shown in the SI. There was a great fluctuation of the five main EEEs from 2008 to 2009 due to the global financial crisis, which led to a decline in EEE demand. China's government introduced a new subsidy program for buying appliances in rural areas in 2009. TV, RE, WM, PC, and AC were sequentially listed in the program, leading to price reduction by as much as 13%. The program was deemed to be a success because the penetration rate increased significantly and the average growth rate of the five major EEEs reached 9.4% in 2010. As shown in Fig. 4, comparing to the penetration rate, the growth rate of in-use stock remains stable before it reaches the maximum value. This phenomenon may be attributed to population growth offsetting the impact of the falling penetration rate.

3.2. The sales and formal recycled EEE in Beijing

The EEE lifespan distribution is shown in the SI. The average lifespan of a refrigerator is the longest (up to 8.5 years), followed by TV, WM and AC (approximately 8 years), and PC (5.2 years due to the very fast upgrading). The sales and obsolete quantities of PC with upper bound are shown in Fig. 5, while those for PC with LB are shown in the SI. There is a large gap between the sales curve and the obsolete curve for each type of the EEE before 2015. However, the latter parts almost coincide, which provides a possibility for achieving a sustainable resource supply of the electronics industry based on recycled materials from WEEE.

Due to the impact of the informal sector, recycled WEEEs from dismantling companies are far less than obsolete EEE. As China's government gradually enhances the capability of law enforcement, WEEE recycling by backyard recyclers will be squeezed out of the market (details in SI). In accordance with the growth rate of 2%, the proportion of formally recycled obsolete EEE will reach 85% in 2037 and will subsequently become stable. The total loss of the five main EEEs that are not formally recycled will be more than 136 million units from 2010 to 2050 in Beijing.

3.3. The sustainable capability of the resource supply

Copper is employed as a case in this article. As discussed above, no obvious changes in the percentage of each resource will occur in the future. Therefore, other kind of resources will also show similar trends of sustainable capability of the resource supply. The average content of copper in WEEE is calculated by Morf et al. and is approximately 41,000 mg/kg (Morf et al., 2007). These data are consistent with the findings of (Oguchi et al., 2012), who showed a range of 18,000–68,000 mg/kg.

The copper demand for electronic production and the supply of secondary copper recycled from WEEE are shown in Fig. 6. The demand shows a downward trend, despite fluctuation, for the population declines and the penetration rate is saturated. And the supply of secondary copper will increase due to the growth of the formal recycling ratio before 2037. Therefore, the gap between them will be rapidly reduced during this period. As shown in Fig. 7 (a), this indicates that the *SSI* will increase and maintain more than 90% of ASD (ASD means the status that the sustainable resource supply has been achieved) after 2037. Interestingly, we have assumed that the formal recycling ratio will increase at the rate of 2% annually and will be stable at a maximum value of 85%. The 2% growth rate continues to 2037. Thus, the formal recycling ratio can determine whether the electronics industry can achieve a sustainable resource supply using secondary-resources recycled from WEEE.

As shown in Fig. 7(a), a downward trend is shown in the demand for primary resources over time. For instance, it will be maintained at less than 1000 tonnes after 2037, which is approximately 15% of that in 2015. However, because the goal of ASD cannot be achieved in the long-term, *PRAC* will continue to increase and cannot reach the maximum after a given year. For the five main EEEs, it will reach 157 thousand tonnes from 2010 to 2050, where AC, with the highest *PRAC*, can reach 59,300 tonnes, followed by RE with 38,700 tonnes, and the others with approximately 20,000 tonnes for each type.

If calculated in accordance with the trend of PC with LB, the results will be very similar to the above ones. As shown in SI, the *SSI* will also increase and maintain more than 90%-ASD after 2037 and *PRAC* will reach 153 thousand tonnes from 2010 to 2050, which is

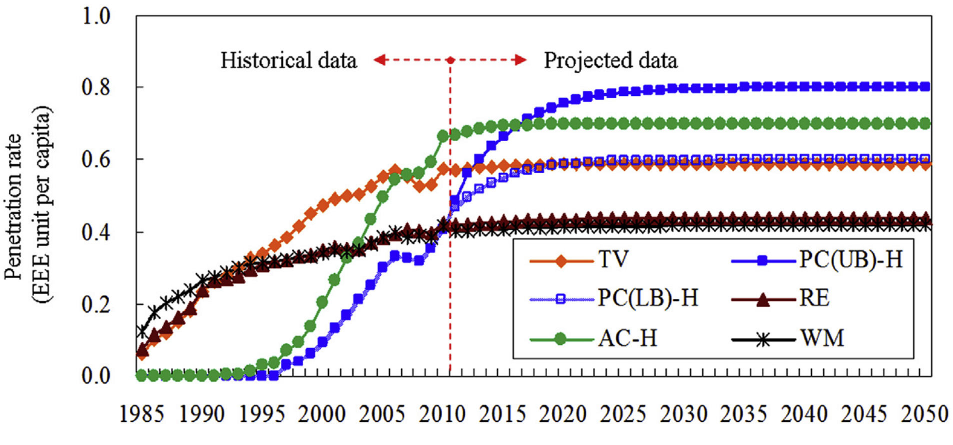


Fig. 3. Penetration rate of household EEE in Beijing.

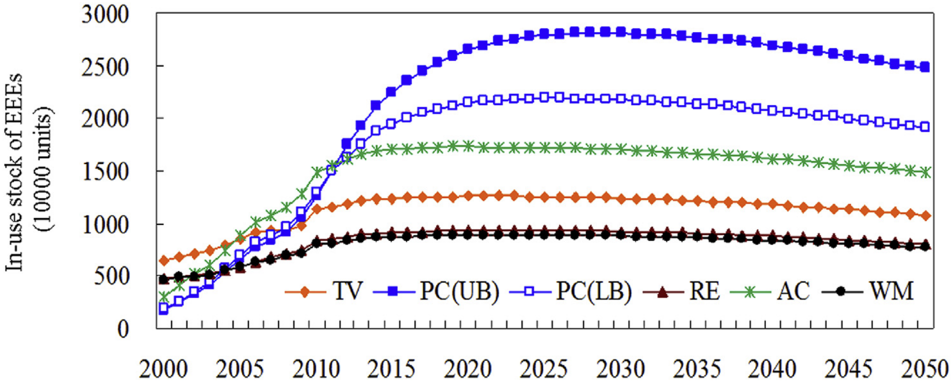
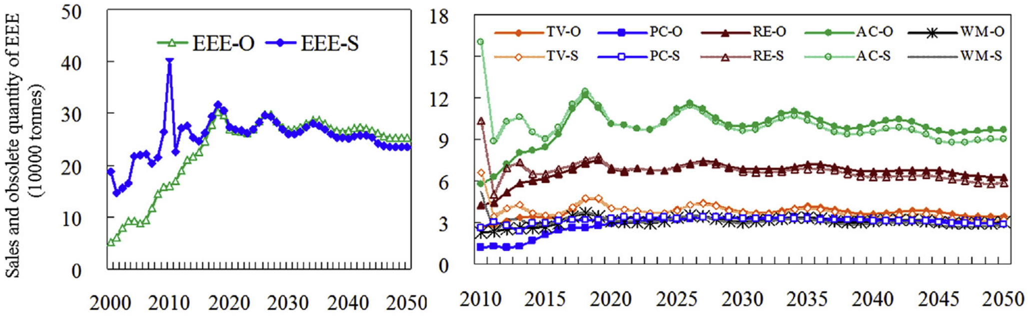


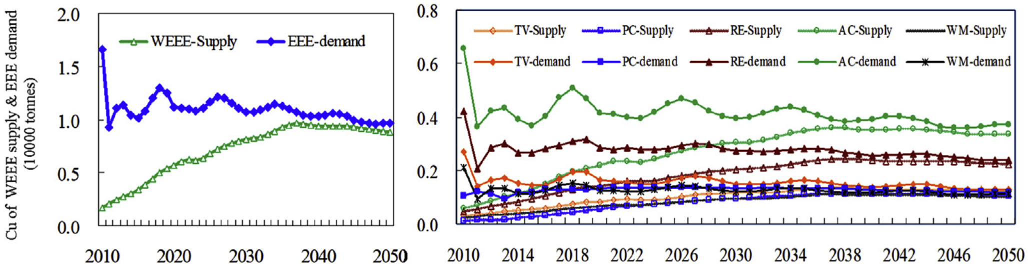
Fig. 4. In-use stock of EEE in Beijing.



(a) Total quantity

(b) Quantity of each type of EEE

Fig. 5. The sales and the obsolete quantity of EEE in Beijing from 2000 to 2050 (In this Figure, *O* here means obsolete, e.g., *RE-O* means the generation amount of obsolete RE. *S* denotes sales, e.g., *RE-S* means the sales quantity of RE.).



(a) Total quantity

(b) Quantity of each type of EEE

Fig. 6. The copper demand for electronics production and the supply of the secondary copper recycled from the WEEE in Beijing from 2010 to 2050.

only 2.5% less than that in the UB case. Therefore, the sustainable capability of resource supply is not sensitive to the selection of the asymptotic value of the penetration rate.

4. Discussion

Four key assumptions in the baseline scenario (BS) discussed above are chosen to analyze the uncertainty of the model: (1) the lifespan of EEE remains unchanged, (2) the formal recycling ratio remains at an annual growth rate of 2%, (3) and is limited to a maximum of 85%, (4) and the quantity of resource content in EEE remains unchanged. As is shown in Table 1, they are reset to determine a better approach to achieve a sustainable resource supply in the electronics industry. Corresponding scenarios, which include the lifespan shortening scenario (LS), the high-speed formal recycling growth scenario (HFRG), the high formal recycling peak scenario (HFRP), and the resource reduction scenario (RR), are used to assess the impact on the *SSI* and *PRAC*.

The sustainable capability of the four scenarios is shown in Fig. 7 (b, c, d, and e). Two guidelines, 90%-ASD and ASD, are set as references to study the impacts on the *SSI* of all of the scenarios. Compared with BS, the LS scenario can promote economic development, as it will increase the sales quantity to 81.4 million units (equivalent to an annual increase of 1.6 million units in Beijing from 2010 to 2050). In the meantime, it will increase the number of formally dismantled WEEE up to 54.3 million units, which can effectively alleviate the overcapacity of the formal sector (CHEARI, 2014). However, the LS scenario will prolong the time to reach 90%-ASD and will increase *PRAC* by 15.3% from 2010 to 2050, which is not conducive for sustainable resource supply.

Compared with BS and LS scenarios, HFRG, HFRP and RR scenarios, however, are beneficial for sustainable development. The

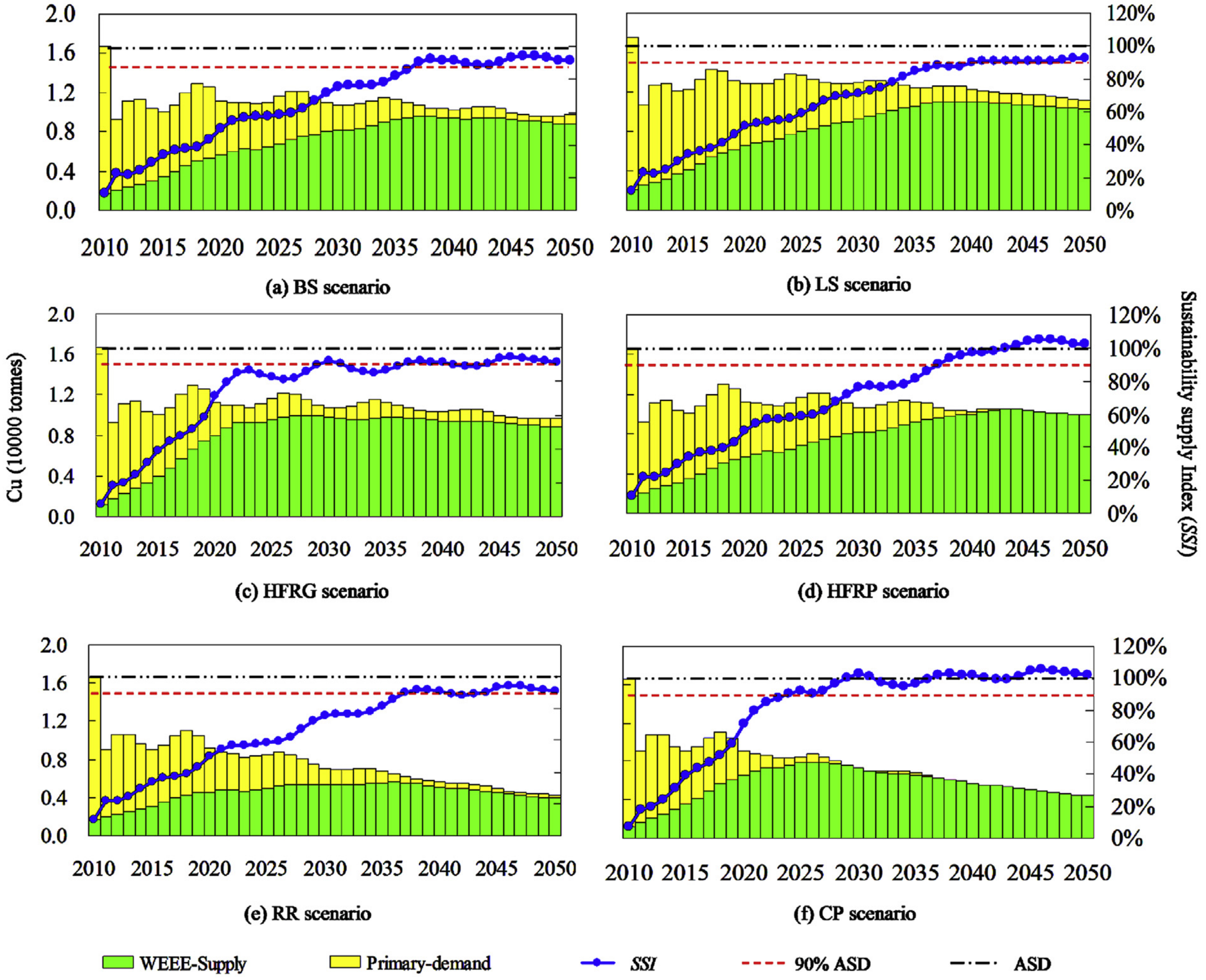


Fig. 7. Comparison of several scenarios of sustainable resource supply.

Table 1
New assumptions and parameter settings.

Scenario	New assumptions	Parameter settings
LS	EEE upgrading will accelerate in the future with a shortening lifespan.	Lifespan distributions of all of the EEEs decrease one-year
HFRG	The construction of the reverse logistics system will be accelerated and backyard recycling will be absolutely banned in China.	The formal recycling ratio will remain at an annual growth rate of 5%
HFRP	Mandatory recycling measures or EPR system will be built in China, which will require consumers to submit their WEEE at designated collection sites before they purchase new EEEs	The formal recycling ratio is limited to a maximum of 95%
RR	China promulgates the resource reduction policy or consumers prefer the lighter EEE design	The quantity of the resources added to EEE will decrease at the rate of 2%

HFRG scenario shortens the time to reach 90%-ASD to approximately 2030 and can reduce the *PRAC* to 118.5 thousand tonnes, which is only 3/4 of that in the BS scenario. The HFRP scenario is the only scenario that can reach the goal of ASD by approximately 2044. However, it cannot reduce the time to reach 90%-ASD, and the *PRAC* is the same as the BS scenario before that time. Therefore the HFRP scenario cannot alleviate as many resource constraints as the HFRG scenario in a short time. The RR scenario can reduce resource inflow of the electronics industry, followed by the *PRAC*. However, the capability of formal recycling is also decreased driven by the lower recycling base. Therefore, the time for reaching 90%-ASD will not change.

According to the different growth rates shown in Fig. 7, the *SSI* curve can be divided into two stages that are separated by the 90%-ASD. A rapid growth is shown in the *SSI* curve before the year when 90%-ASD is reached, whereas the growth rate slows down after the year.

Thus, the key to achieve a sustainable resource supply in the electronics industry is to reduce the time to reach 90%-ASD, to achieve the ASD in the long-term, and to minimize *PRAC*. As shown in Table 1, the best approach is to extend or maintain the lifespan of EEE by propaganda and education, to ban backyard recycling by strict environmental standards, to improve the overall recovery efficiency by building a closed-loop supply chain, and to reduce resource content by eco-design. A combined policy (CP) scenario can be defined, integrating the BS, HFRG, HFRP, RR scenarios. As shown in Fig. 7 (f), the CP scenario dramatically shortens the time to achieve a sustainable resource supply. The 90%-ASD and ASD will achieved in 2024 and 2029. *PRAC* is only 81.3 thousand tonnes, which is almost half the primary resource consumption compared to the BS scenario from 2010 to 2050. Moreover, *PRAC* will remain at a negative value from 2037 to 2050, which means that a sustainable resource supply of the electronics industry will be achieved by 2037.

To achieve the CP scenario, in addition to long-term flexible propaganda and education, it is essential to find a way to improve the formal recycling rate and its maximum limitation. Currently, two ways can be selected. The first is to enact laws and regulations to manage the recovery process, which will indirectly reduce informal recycling. For example, the EU issued WEEE and RoHS directives to build an EPR system that requires producers to set up and operate individual and/or collective take-back systems for WEEE from private households (European Union, 2011, 2012). The other is to manage the recycling process directly, and a national processing fund has been established to subsidize formal dismantling companies. In addition to government oversight, this mode also relies on market mechanisms to eliminate backyard recyclers (Gu et al., 2016). The most typical representative is China, which began to implement the “waste electrical and electronic products processing fund” in 2012, and the process of collection and distribution of the fund is shown in the SI. For example, 13 RMB/unit is collected from producers and is used to subsidize formal dismantling companies by 85 RMB/unit for television. This finding means the subsidy standard is approximately 4.5 times higher than the collection standard. This model has indeed promoted the enthusiasm of formal recyclers. China had approved 109 formal dismantling companies by the end of 2015.

However, on the one hand, this funding system cannot achieve a stable supply of the subsidy and will lead to severe financial pressure on the government in the long-term. As shown in SI, the fund that is distributed is always larger than the fund that is collected, and the gap will continue to widen before 2028 in Beijing. Although regional differences do exist and will affect the fund balance in China, the overall trends of the sales curve and the formal recycling curve are consistent, which indicates the fund cannot achieve a long-term sustainable supply.

On the other hand, the funding system cannot improve the formal recycling rate over the long-term because it cannot regulate and will even intensify confusion in the recovery process. First, formal dismantling companies urgently need a stable supply of WEEE due to their serious overcapacity, and the only way to solve this problem is to increase the procurement price of WEEE. Thus, the fund is mostly shared by WEEE collectors, enhancing their profitability, and resulting in more companies willing to enter the recovery and recycling industry (Gu et al., 2016). In 2013, the number of the registered recovery companies was up to more than 100 thousand. Coupled with door-to-door peddlers, the total number of collectors is huge, but scattered. Second, these collectors' choices of target customers are entirely determined by the price. Compared with formal dismantling companies, these backyard recyclers are the main source of pollution in the recycling industry (Chi et al., 2011; Williams et al., 2008), and have no incentive to pay fees to control pollution and upgrade their technology and equipment, resulting in the profit of backyard recyclers being higher than formal ones. Thus, the fund can only temporarily improve the competitiveness of formal recyclers. However, once the fund is done away with or the subsidies are too low to eliminate backyard recyclers, they will also occupy the recycling market.

5. Conclusion

High consumption of EEE is accompanied with a high yield of WEEE. Meanwhile, because the different types of resources have their own unique properties, the current content of each type will remain limited in a range of fluctuations. Therefore, WEEE recycling is an obvious choice to meet the resource demands of the electronics industry. In this article, a dynamic sustainable supply model was used to measure whether a sustainable resource supply of the electronics industry can be achieved using secondary-resources recycled from WEEE. In order to measure the uncertainty of the model, four scenarios which changed one of the key assumptions of the model were used to assess the impact on the *SSI* and *PRAC*. These four scenarios are lifespan shortening scenario, high-speed formal recycling growth scenario, high formal recycling peak scenario, and the resource reduction scenario. Subsequently, a combined policy scenario based on their advantages is built and demonstrated to be a feasible method to achieve a sustainable resource supply using recycled resources. A high-speed formal recycling growth and a high formal recycling peak are proved to be vital in the achievement of this scenario. Government policy support is necessary to do so. However, the policy of the funding system in China can only be used as an assistant policy because it is unsustainable and cannot fundamentally squeeze backyard recyclers out of the market. The EPR system, which completely relies on government oversight, can be employed to improve the formal waste recycle network system in the long run, and in this way, a sustainable resource supply will be achieved by 2037 in Beijing, China.

Acknowledgments

The authors gratefully acknowledge the financial support from Beijing Nova Program, National Natural Science Foundation of China (No.71273021), Academician Workstation in Yunnan Province, and Interdisciplinary Beijing Municipal Key Discipline, “Resources, Environment and Recycling Economy” Project (033000541214001).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.04.041.

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