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ORIGINAL ARTICLE

Resource-availability scenario analysis for formal and informal recycling of end-of-life electrical and electronic equipment in China

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Abstract In strategic end-of-life electrical and electronic equipment (EoL EEE) management, it has become important to not only avoid the negative environmental impacts but also enhance the positive effects of secondary resource utilization. This is especially true in emerging countries such as China, where medium- to long-term increases in the amount of EoL EEE generation are projected. This study aims to assess the resource availability potential for EoL EEE recycling based on penetration scenarios for formal and/or informal treatment options in China. We categorized substances contained in EoL television sets and personal computers into environmental, resource, and economic aspects under consideration of product transitions. Barium and copper have a high negative potential impact on human health and/or the ecosystem. Focusing on metals with a high resource potential, the resource availability is assessed under different treatment options using characterization factors identified through a life-cycle impact assessment method, the ReCiPe 2008. The results suggest that copper and lead recycling could alleviate the increase in mining costs of resource utilization. Scenario analysis for penetration of formal and informal recycling options indicated that the difference in the alleviated mining costs between the status quo and short-term transition projections until 2030 corresponds to 2.1–2.4 billion dollars.

Keywords Resource availability · Environmental impact · Management scenarios · End-of-life electrical and electronic equipment · China

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Introduction

End-of-life electrical and electronic equipment (EoL EEE), also called waste electrical and electronic equipment (WEEE or e-waste), has received a lot of attention because EoL EEE poses a significant threat to both the natural environment and human health when it is unprocessed or processed without adequate control [1–4]. Conversely, EoL EEE contains very valuable and rare materials, which can be retrieved through adequate recycling. EoL EEE contains more than 1000 different substances, many of which are potential environmental contaminants; such as lead (Pb), antimony (Sb), mercury (Hg), arsenic (As), cadmium (Cd), nickel (Ni), selenium (Se), hexavalent chromium (Cr(VI)), flame retardants, polybrominated diphenyl ethers (PBDEs), and polychlorinated biphenyls (PCBs) [5–7]. These toxins can cause brain damage, allergic reactions, and cancer if excessively absorbed by human [8]. In addition, EoL EEE contains valuable materials such as plastic and metals including common, less common, and precious metals as secondary resources [9, 10]. Secondary resource recycling is thus driven by the value of the recovered metals (and materials). Usually, metallurgical plants try to recover all the valuable elements as far as there is an economic incentive [11].

In China, the increasing purchasing power coupled with technical innovations of EEE has accelerated the consumption of EEE and, consequently, the generation of EoL EEE. It was estimated that the total generation of EoL household television (TV) sets, refrigerators, washing machines, air conditioners, and personal computers (PCs) in 2030 will be 2.5 times larger than that in 2010 [9]. However, as far as policies and legislations are concerned, China has little experience in managing EoL EEE recycling and treatment when compared with more developed countries such as Japan. Moreover, China is facing severe challenges in addressing the negative impacts resulting from improper EoL EEE treatment [12]. To date, the formal recycling sectors in China have not succeeded in competing with the informal sectors, most notably in the amounts for treatment and the cost for recovery [12–15]. In addition, outdated recycling and treatment methods are applied in the informal sectors, whereas man–machine processes are implemented in the formal sectors [14, 15]. In China, to address the aforementioned problems, such as current widespread treatment in informal sectors and the huge amounts of EoL EEE generated in the near future, it has become increasingly important to not only avoid negative impacts on the ecosystem and human health but also strengthen the positive effects on secondary resource utilization. Therefore, EoL EEE management has assumed a win–win strategy.

Some research groups have focused on the secondary metal resources obtained from EoL EEE [9, 16–20]. Tasaki et al. [18] presented three indices (resource consumption, water pollution influencing human health, and aquatic biota conservation) for screening 36 metals in EoL EEE using simple assessment methods. Besides, Song et al. [21] conducted a life-cycle assessment study to investigate the environmental impact of a formal e-waste treatment enterprise. However, several toxic, valuable, and precious metals in Chinese EoL EEE have rarely been assessed, and there is no quantitative assessment of the above indices for EoL EEE management in China.

To date, technological innovation that has accelerated the transition of substance contents in electronic products has significantly influenced the evaluation of the environmental impact potential [22] as well as the EoL EEE's strategic management. Therefore, an environmental and resource impact analysis should consider the products' technology transitions to guide the pollution prevention strategies aimed at reducing the impact of toxins and to provide information on the valuable materials' recovery priority during the disposal and treatment practices in China. Thus, the objective of the current study is to assess the resource availability potential of EoL EEE recycling based on penetration scenarios for formal/informal recovery and different treatment options. The anticipated results are expected to support EoL EEE management decision making in China. In the present study, first, the substances contained in EoL TV-sets and PCs are categorized into environmental, resource, and economic perspectives, considering the products' technology transitions. Focusing on metals with a high resource potential, the resource availability is assessed for different recovery and treatment options using the characterization factors identified through a life-cycle impact assessment (LCIA) method. Penetration scenarios for formal and informal tactics and the difference in alleviated mining costs between the status quo and the 2030 transition-scenarios are evaluated.

Materials and methods

Categories of metals contained in EoL EEE in China

Among the EoL EEE, different types of EoL TV-sets including cathode ray tube (CRT), plasma display panel (PDP) and liquid crystal display (LCD) TV-set and PCs including desktop and laptop PC were chosen as targets because of the following reasons: (I) TV-sets are the most frequently owned EEE in households, and PCs have the shortest lifespans [9] and (II) the materials contained in these EEE present high resource shortage potentials and are environmental contaminants. The data in terms of substance contents of EoL TV-sets and PCs are very limited and fragmented. The individual data from published papers and technical reports [17–19, 25, 30–33] were collected as far as possible. On a total, 16 metals were analyzed, including common metals such as aluminum (Al), copper (Cu), iron (Fe), tin (Sn), zinc (Zn), nickel (Ni), and lead (Pb); less common metals such as barium (Ba), bismuth (Bi), cobalt (Co), antimony (Sb), mercury (Hg), and strontium (Sr); and precious metals such as silver (Ag), gold (Au), and palladium (Pd). These metals are contained in TV-sets and PCs, and controversial from the environmental and resource viewpoints [9].

According to Habuer et al. [9], based on the generated amounts, the module compositions, and the substance contents of each module, the substance content of EoL EEE in year t can be calculated using Eq. (1).

$$\begin{aligned}\text{Substance content of EoL EEE } (t) &= \sum_i \text{weight of module } i \text{ of EoL EEE } (t) \\ &\quad \times \text{substance content of module } i,\end{aligned} \tag{1}$$

where i indicates different modules. The weight of module i of an EoL EEE in year t can be calculated using Eq. (2).

$$\begin{aligned}\text{Weight of module } i \text{ of EoL EEE } (t) \\ = \text{generation amount of EoL EEE } (t) \\ \times \text{average weight of EoL EEE} \\ \times \text{module composition}\end{aligned} \quad (2)$$

The metal content in EoL TV-sets in China has been estimated until the year 2030 [9]. The generated amounts in different types of EoL PCs can be calculated using the EoL PCs types' market shares and the method provided by Habuer et al. [9]. By fitting with historical market-share data [23, 24], the future market share ratio of desktop and laptop PCs can be obtained, assuming that desktop PC will still remain on 10 % of the whole PC market-share at least until 2030 (see SI Fig. S1). In addition, the data on average weights, module compositions, and metal contents of each module in desktop and laptop PCs were collected from published papers, technical reports, and relevant documents [17–19, 25–33] (see SI Table S1-S3). The median values of the module compositions as well as metal contents in respective modules were applied. There are many characterization models developed for LCIA, either using simple indicators with simplified model or streamlined model simulations, such as EDIP 97 [34], CML 2002 [35], Eco-indicator 99 [36], IMPACT 2002+ [37], LIME 2 [38], ReCiPe 2008 [39]. In this study, 16 metal categories are separated on the basis of their damage (endpoint) factors (DFs) in ReCiPe 2008 [39] and their 2010–2030 cumulative generation amounts in China to identify the metals that potentially have high impacts as secondary materials. The DFs include "damage to human health (HH)" evaluated as disability-adjusted life years (DALY); "damage to ecosystem diversity (ED)" evaluated as loss of species during a year; and "damage to resource availability (RA)" evaluated as the future increase in mining costs. The ED and HH factors for the discharge of soil have been considered for most metals in EoL TV-sets and PCs, and they are landfilled informally. Conversely, the RA factor has been used in evaluating the positive effects of recycling, assuming that negative impacts (mining costs) due to the primary resource consumption would be alleviated by the recovery of the same type of secondary materials. The unit of DFs in RA is \$/kg, e.g., DF value of iron is 0.07 \$/kg and DF value of copper is 3 \$/kg. Furthermore, secondary materials have also been categorized by the current market values (MVs), which would provide the necessary incentive for their recovery [40–43]. The RA factors are not available in ReCiPe 2008 for Ba, Bi, Sb, Hg, and Sr; therefore, those metals have been disregarded in the RA assessment. Similarly, Bi, Au, and Pd have been ignored in both the ED and the HH factor assessment. Moreover, the current MVs of Ba, Hg, and Sr are not available.

Resource availability assessment under the different recovery and treatment options in China

A field survey was conducted on February 20–March 8, 2012 in Beijing, China, by five experts, including three professors and two representatives of the Chinese Household Appliances Association and the China Resource Recycling Association. Besides, one formal treatment facility was investigated, as well as five second-hand electronic markets and several individual collectors. In addition to the field survey and the literature review, the feasible recovery and the possible treatment options of EoL TV-sets and PCs were investigated. Figures 1 and 2 present the conceptual flowcharts under the different recovery and treatment process options. The recovery and treatment option I (hereafter called as option I) is a rudimentary treatment method (informal treatment process) mainly used in developing countries such as China, Philippine, and Vietnam [44]. The recovery and treatment option II (hereafter called as option II) refers to advanced processes mainly used in developed countries, such as Japan, as well as in a few advanced (pilot) formal treatment plants in China. In option I, EoL TV-sets and PCs after manual dismantling are separated into printed circuit-boards (PC Boards), drives, cables, mixed metallic scraps, liquid crystal display (LCD) panels, plastics, parts (transformers and laud speakers), and residues. The mixture comprising metallic scraps, LCD panels, and plastics can be recycled, and the parts (transformers and laud speakers) can be reused. PC Boards and drives with the obsolete mechanical processes, such as heating boards and harmer smashing, can be divided into electronic components, substrate, and IC chips. Furthermore, substrate and IC chips are treated using outdated hydrometallurgical processes such as acid leaching to extract the precious metals. Besides, cables are open-burned, under this option, in order to gain the copper metals. Residues including cathode ray tube (CRT) glasses in this option whose recycling does not offer any economic profit for informal sites are eventually through-outed or open-burned in the nearby treatment yards (see Fig. 1). In option II, EoL TV-sets and PCs after manual dismantling are separated into PC Boards, drives, cables, CRT glasses, metallic parts, LCD panels, plastics, transformers, loud speakers, cold cathode fluorescent lamps (CCFLs), and batteries. Some parts such as transformers and loud speakers are forwarded to downstream manufactures for reuse, whereas others are treated through various mechanical processes including shredding, eddy current separating, cutting, and gravity separation (Fig. 2). Furthermore, the substrate and the IC chips undergo pyrometallurgical and hydrometallurgical processes (option II-a) or physical processes (option II-b) to extract the precious metals. In addition, the mercury distillation

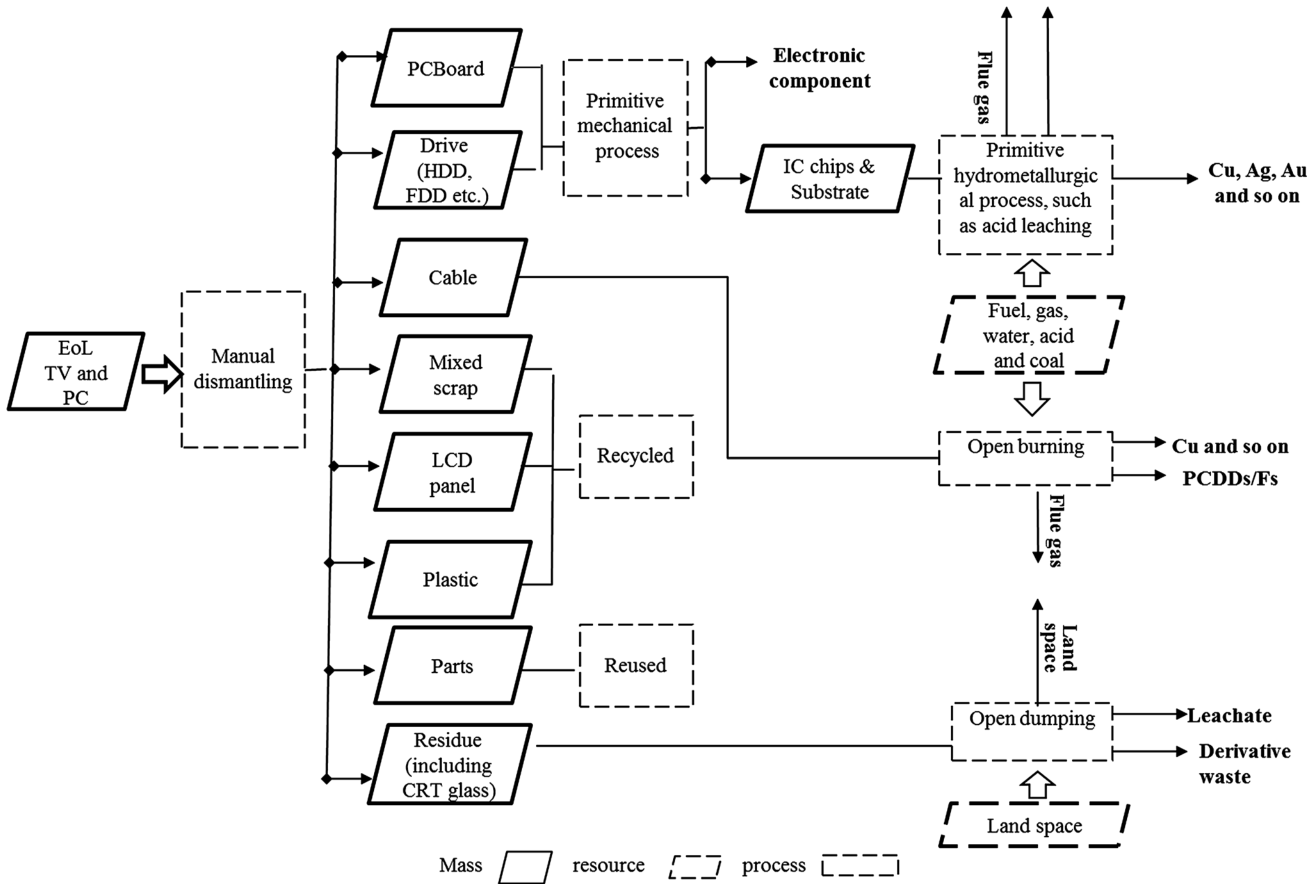


Fig. 1 Flowchart of the recovery and treatment option I

process is applied to phosphors, which contain harmful substances, to recover the mercury. Residues without economic value are not recovered, and are eventually landfilled.

To evaluate the potential effects of recycling on resource availability, the inflow and outflow of EoL CRT and LCD TV-sets are calculated in various unit processes included in the three options. This calculation uses the metal contents and the maximum recovery efficiencies and considers the larger amount of EoL TV-sets being treated in China, in comparison with EoL PCs. It assumes that 100 % metal inflows in each processing unit could be recovered for evaluation of potential effects on resource availability. Therefore, the maximum effects, i.e., RA alleviation, of different options can be obtained by Eq. (3).

$$\text{Alleviation of RA} = \sum_i \text{DF of metal } i \times \text{weight of metal } i \text{ contained in EoL TV - set,} \qquad (3)$$

where i indicates the different metals contained in EoL TV-sets. The alleviation of RA corresponds to the alleviated mining costs ($), and DF indicates damage factors of RA ($/kg).

EoL EEE management scenarios' assessment

The most important key factor for successful EoL EEE management in China today refers to the potential for sufficient EoL EEE to be collected and treated through formal methods. The funds for EoL EEE recovery and disposal provided by EEE manufacturers, importers, and their agents under the policy of Extended Producer Responsibility (EPR) only partially cover the formal treatment sites' costs. In addition, these provided funds depend on sales, and fund allocation is based on the amount of EEEs being formal treated. If formal sites cannot collect enough quantity for treatment, this strategy will not be considered successful for EoL EEE management. In addition, funds may contribute to the informal sites' cost in an attempt to improve the applied techniques and to convert the informal to formal treatment. This could be a win–win strategy, providing advantages for both pollution prevention and resource recovery. Thus, an EoL EEE management scenario analysis was conducted to identify the alleviation of mining costs based on different scenarios. It is noteworthy that, according to the definition of RA, only mining saving costs through recovery of secondary

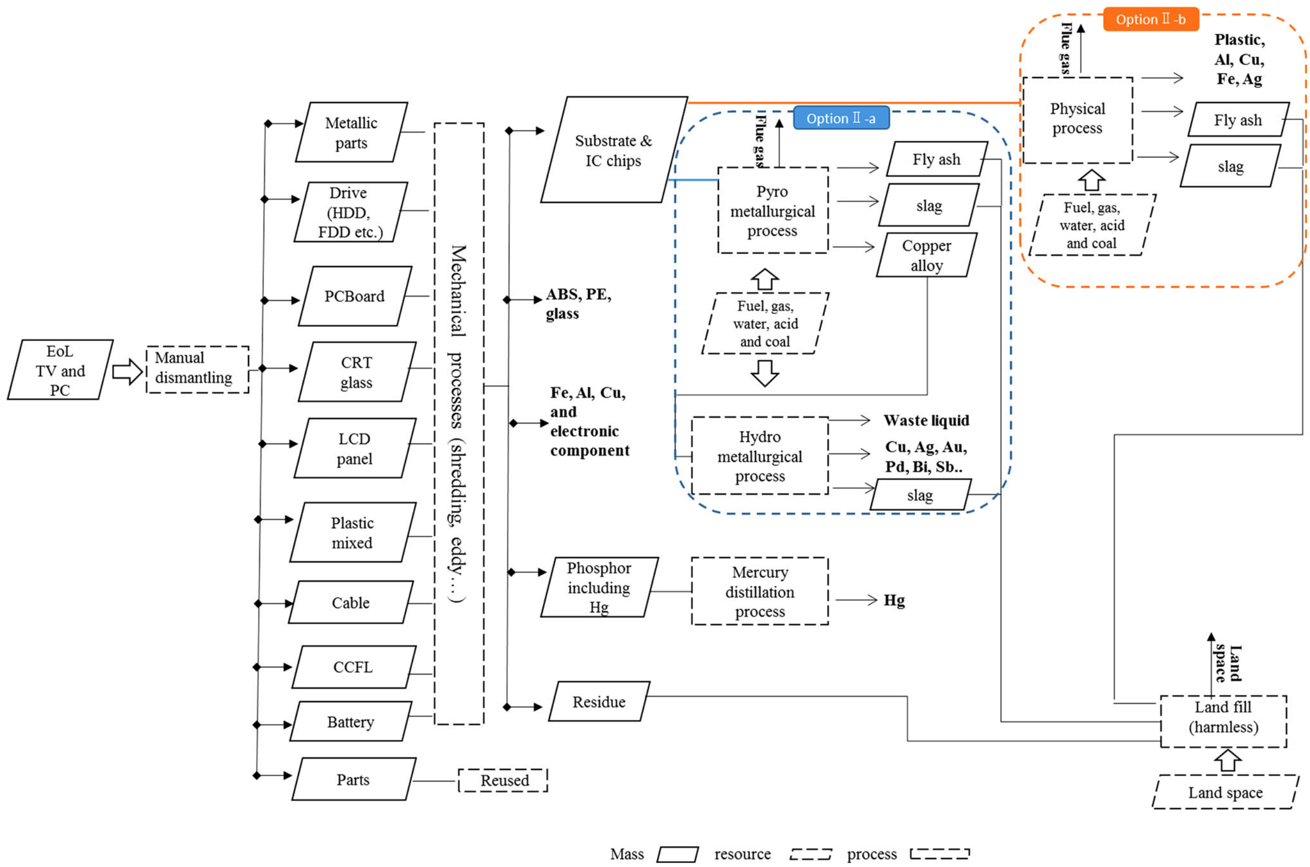


Fig. 2 Flowchart of the recovery and treatment options II-a and II-b

materials were considered in this study. The scenarios are given below.

Scenario 1 (S1) Option I (informal) gradually converted to option II-a (advanced formal) facilitated by leading-in technical innovation and government subsidy during the year 2000–2030

Scenario 2 (S2) Option I (informal) sharply converted to option II-a (advanced formal) facilitated by leading-in technical innovation and government subsidy during the year 2000–2020

Scenario 3 (S3) Option I (informal) slowly (laxly) or unchangeably converted to option II-a (advanced formal) without government participation to the costs or other direct benefits from the conversion during the year 2000–2030

There are several assumptions based on the EoL EEE management social policy factors in China: (1) The EoL EEE was treated completely at informal sites in 2000–2004; (2) Although most EoL EEE was still treated at informal sites, there were certain amounts treated at formal sites during the implementation of the pilot project and the "Old for New" project (2004–2012). According to that the amount of EoL EEE formal dismantling in 2011 was accounted for 7 % of the total obsoleted EoL EEE [9, 15], it is assumed that until the end of 2012, almost 10 % of the obsoleted EoL EEE had been treated by the formal sector; (3) The conversion from the informal to the formal treatment is facilitated by leading-in technical innovation and government subsidy, and informal sites have never been converted to formal ones without government participation to the costs or other direct benefits from the conversion.

On the basis of scenario settings and assumptions, the penetration curves for the three scenarios are presented in Fig. 3. The penetration curves for the three examined scenarios are considered to be the most prominent factors that affect the prediction results. Therefore, for validating the uncertainty of prediction results by changing the values of parameters which dependent on assumptions, logistic curve and linear curve during the year 2013–2030 were used for the three examined scenarios.

Results and discussion

EoL TV-sets and PCs metal content in China

The generation of EoL TV-sets in 2010 was already 21 times greater, by weight, than that in 2000; the generation of EoL TV-sets in 2030 is expected to 2.4 times greater, by weight, than that in 2010 [9]. The total discarded weight of desktop PCs was 366 thousand metric tons in 2010: the main units corresponded to 134 thousand metric tons, the LCD monitors to 93 thousand metric tons, and the CRT monitors to 139 thousand metric tons (see SI Fig. S2). The total discarded weight of laptop PCs was 83 thousand metric tons, and the total weights of PCs amounted to 449 thousand metric tons in 2010 (Fig. 4). EoL desktop PCs remain much larger proportion in the obsolescence by weight before 2010; and the proportion will decrease year by year due to the increasing amount of EoL laptop PCs. EoL PC generation, by weight, in 2010 was 10 times greater than that in 2000; EoL PC generation in 2030 is expected to 1.2 times greater, by weight, than that in 2010 (Fig. 4). Most metals' contents in EoL TV-sets and PCs per year are expected to increase. However, less common metals (except Hg) and common metals such as Cu, Ni, and Pb are expected to decrease their content in EoL TV-sets over the next 15 years [9]. A significant increase per year is anticipated in the Ni, Al, Hg, Au, Pd, Co, and Bi content of EoL PCs (Fig. 5 and SI Fig. S4). Other metal contents in EoL PCs per year are available in SI Fig. S3-4.

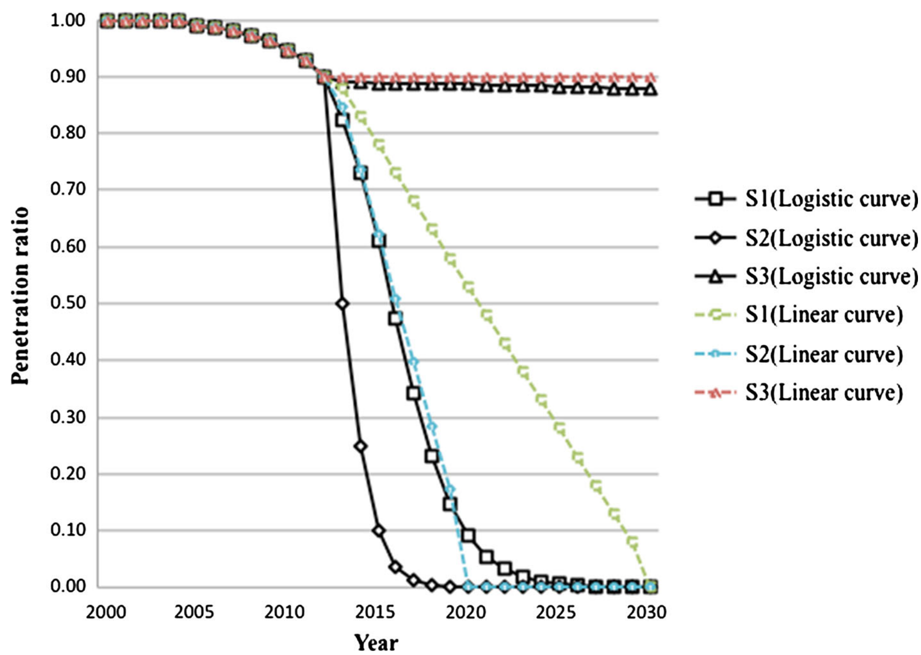


Fig. 3 Penetration curves for the three examined scenarios: option I is shifted in relation to option II-a in the three scenarios

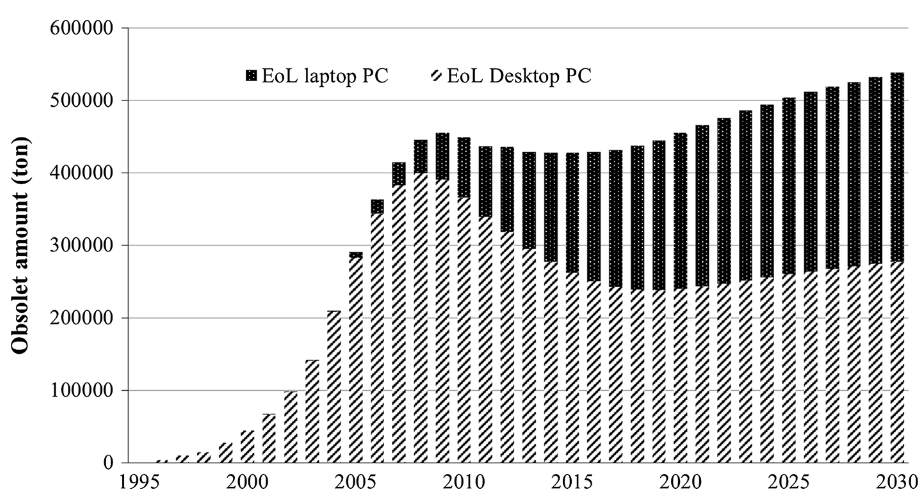


Fig. 4 Obsolescence of different EoL PC types by weight

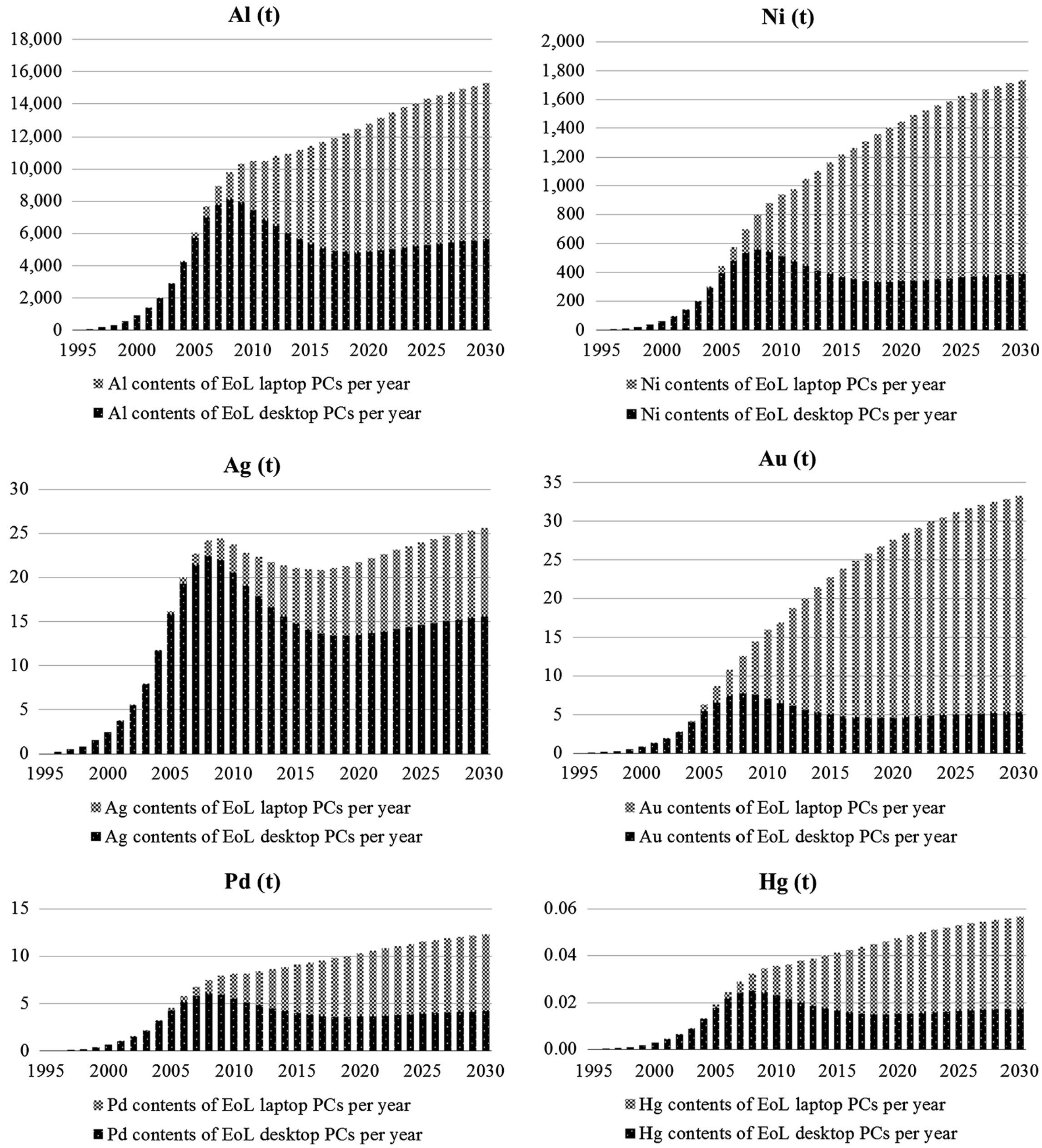
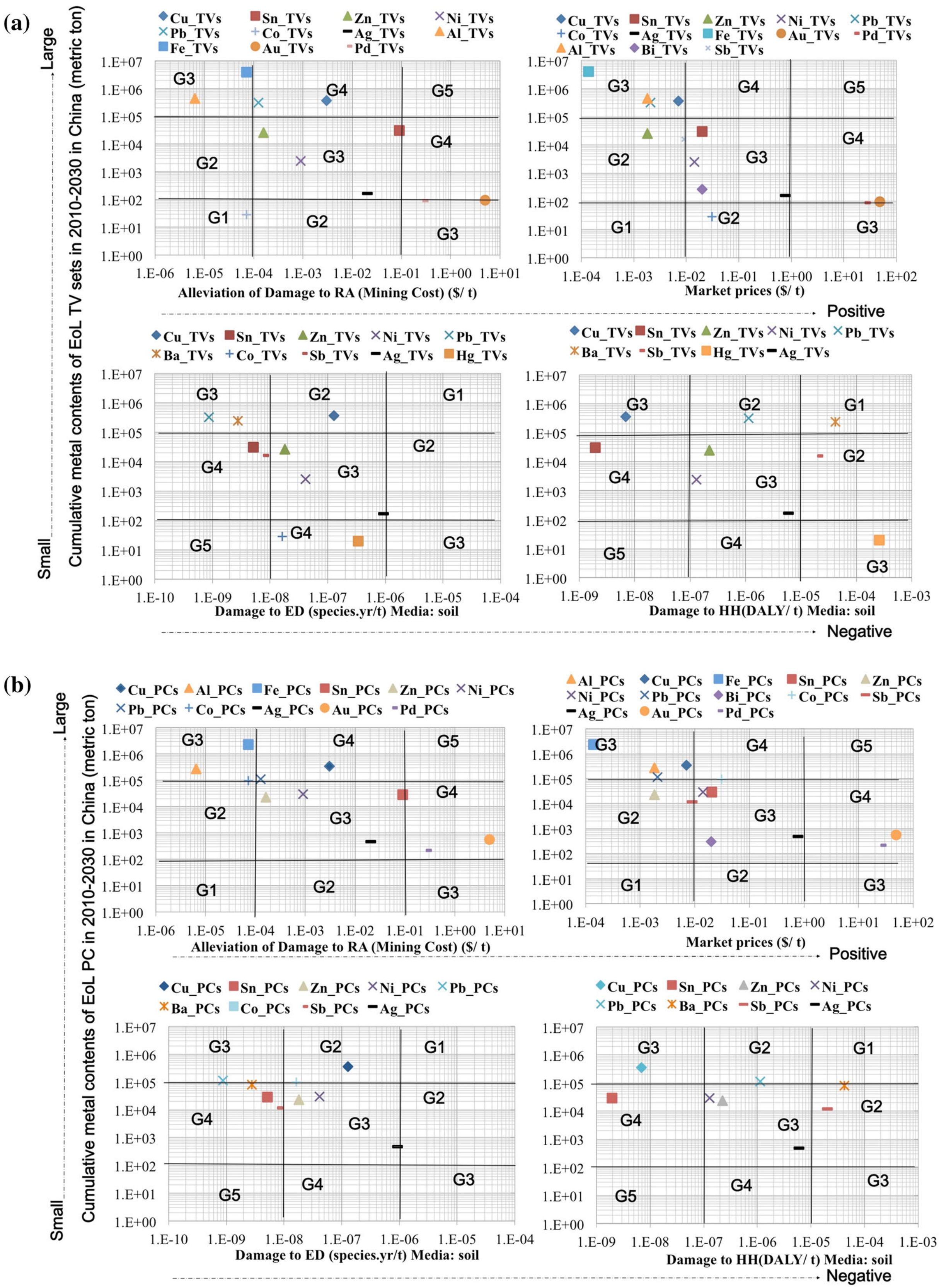


Fig. 5 Selected metal contents in the annually generated EoL PCs

Consequently, EoL TV-sets and PCs are expected to form a considerable urban mine with high resource potential.

Categorization of metals contained in EoL TV-sets and PCs generated in 2010–2030 in China

Figure 6 presents the metal categories that are based on DFs and the estimated cumulative generation amounts of EoL TV-sets and PCs for 2010–2030. The characteristics of each group are presented in SI Table S4. The summary of categorization of metals in Fig. 6 is also shown in Table S5. Less common metals such as Sr and Ba will be largely contained in both EoL TV-sets and PCs discarded between the years 2010–2030. Apart from precious metals, Hg and Bi content will be less contained in both EoL TV-sets and PCs. Precious metals and Co will be largely contained in EoL PCs discarded between the years 2010–2030, as compared with EoL TV-sets. The present results indicate that Ba, Sb, and Pb contained in both EoL TV-sets and PCs have a high negative potential impact to HH through discharge to soil. Cu in EoL PCs also retains a relatively high negative potential impact to ED through discharge to soil. Co in EoL TV-sets has low potentials for RA and resource recovery, whereas it has low negative


(a)
Large
Small
Cumulative metal contents of EoL TV sets in 2010-2030 in China (metric ton)
Cu_TVs Sn_TVs Zn_TVs Ni_TVs Pb_TVs Co_TVs Ag_TVs Al_TVs Fe_TVs Au_TVs Pd_TVs
G1 G2 G3 G4 G5
Alleviation of Damage to RA (Mining Cost) ($/ t)
Cu_TVs Sn_TVs Zn_TVs Ni_TVs Pb_TVs Co_TVs Ag_TVs Fe_TVs Au_TVs Pd_TVs Al_TVs Bi_TVs Sb_TVs
Market prices ($/ t)
Positive
Cu_TVs Sn_TVs Zn_TVs Ni_TVs Pb_TVs Ba_TVs Co_TVs Sb_TVs Ag_TVs Hg_TVs
Damage to ED (species.yr/t) Media: soil
Cu_TVs Sn_TVs Zn_TVs Ni_TVs Pb_TVs Ba_TVs Sb_TVs Hg_TVs Ag_TVs
Damage to HH(DALY/ t) Media: soil
Negative
(b)
Large
Small
Cumulative metal contents of EoL PC in 2010-2030 in China (metric ton)
Cu_PCs Al_PCs Fe_PCs Sn_PCs Zn_PCs Ni_PCs Pb_PCs Co_PCs Ag_PCs Au_PCs Pd_PCs
Alleviation of Damage to RA (Mining Cost) ($/ t)
Al_PCs Cu_PCs Fe_PCs Sn_PCs Zn_PCs Ni_PCs Pb_PCs Bi_PCs Co_PCs Sb_PCs Ag_PCs Au_PCs Pd_PCs
Market prices ($/ t)
Positive
Cu_PCs Sn_PCs Zn_PCs Ni_PCs Pb_PCs Ba_PCs Co_PCs Sb_PCs Ag_PCs
Damage to ED (species.yr/t) Media: soil
Cu_PCs Sn_PCs Zn_PCs Ni_PCs Pb_PCs Ba_PCs Sb_PCs Ag_PCs
Damage to HH(DALY/ t) Media: soil
Negative

◀ **Fig. 6** **a** Categorization of the metals contained in EoL TV-sets in 2010–2030 in China. **b** Categorization of the metals contained in EoL PCs in 2010–2030 in China

potential environmental impacts (both HH and ED). Therefore, Co in EoL TV-sets may not necessary for the recovery and recycling. Cu and Pb contained in EoL TV-sets, Pb, Cu, Pd, and Au contained in EoL PCs have relatively high potentials for RA. In addition, Pd and Au contained in EoL PCs have a high market value. Thus, there is a high incentive for their recovery and consequently it can alleviate damages to RA.

Resource availability under different recovery and treatment options

Inflow and outflow per unit weight of EoL CRT TV-sets in option II-a are presented in Fig. 7. The abbreviations of each process are listed in Table 1. The other inflow and outflow of CRT and LCD TV-sets are presented in SI Figs. S5-9. In option I, valuable materials accounting for approximately half of the EoL CRT TV-sets' total weight and approximately 90 % of the EoL LCD TV-sets' total weight will be reused or recycled by the downstream manufactures through the primitive mechanical and pyrometallurgical processes. They are mixed scraps, plastics, electronic components, transformers, loud speakers, LCD panels, and metals. The residues, which are over half of the EoL CRT TV-sets' total weight and over 10 % of the EoL LCD TV-sets' total weight will be open-dumped. This process is expected to incur severe environmental impact. Alternatively, processing through the advanced treatment methods proposed in options II-a and II-b, the most valuable materials in the modules may be recycled or reused by the downstream manufactures. Less than 5 % of the EoL CRTs' and LCD TV-sets' total weight will be forwarded to the landfill. Nevertheless, the upgraded pyrometallurgical and hydrometallurgical processes have relatively higher electricity demands.

The alleviated mining costs following the three options are correlated with the maximum metal contents, as shown in Fig. 8. It is estimated that, when the maximum metal contents from 100 kg of EoL CRT TV-sets are

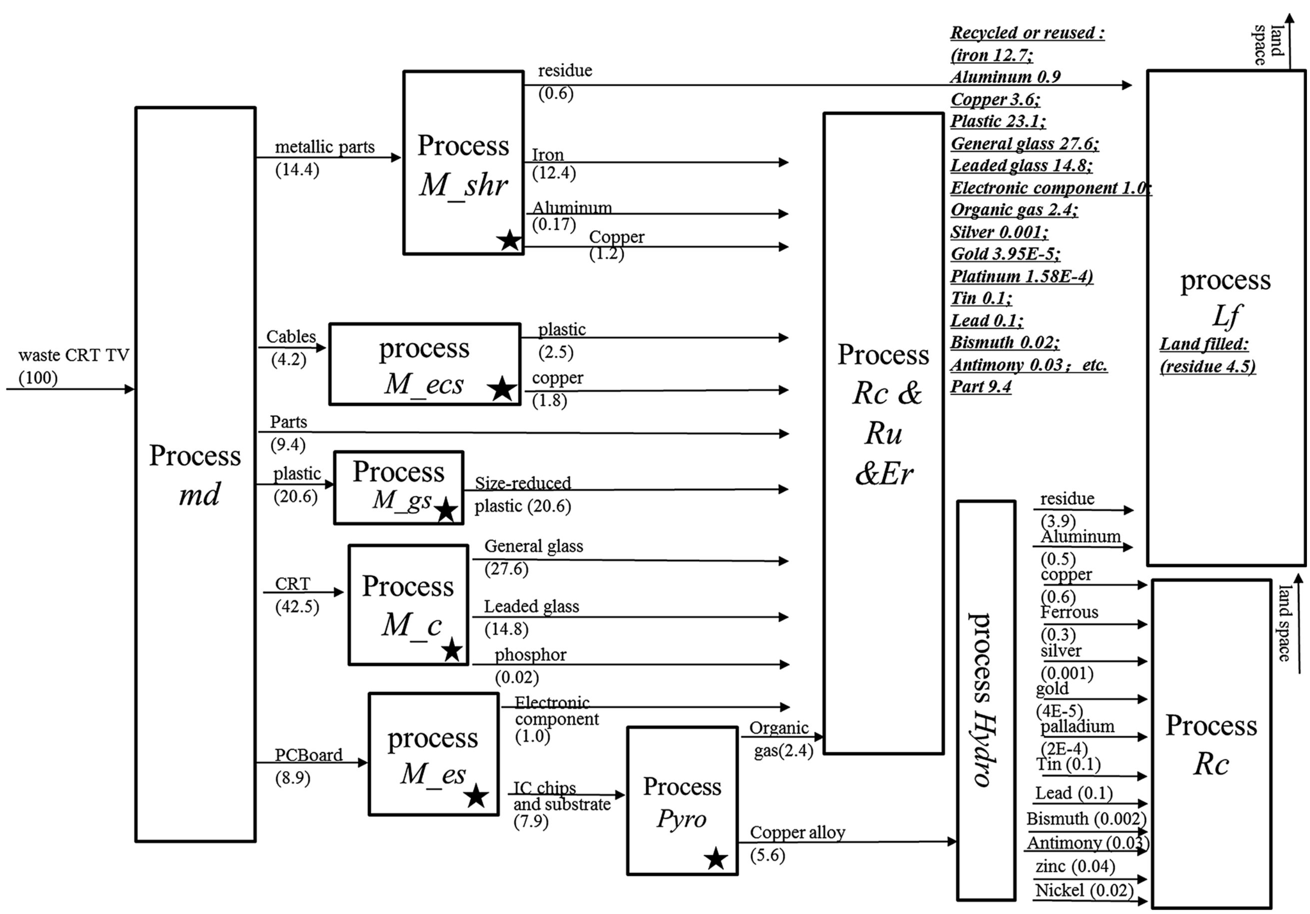


Fig. 7 Inflow and outflow per unit weight of EoL CRT TV-sets in option II-a

Table 1 The abbreviations of recycling and treatment processes of EoL TV-sets

Abbreviation	Processes
md	Manual dismantling and separation
pM	Primitive (outdated) physical mechanical process
pM_hs	Hammer smashing
pM_hb	Heating board
M	Physical mechanical process (including shredding, packaging, axed cutting, eddy current separation, magnetic and gravity separation)
M_shr	Shredding and packaging
M_gs	Shredding and gravity separation
M_es	Electronic component separation
M_c	Cutting and shredding
M_ecs	Shredding and eddy current separation
M_mr	Mechanical separation and mercury recovery
pC	Primitive chemical process
pPyro	Open burning
pHydro	Primitive hydrometallurgical process (such as acid leaching)
C	Chemical process
Pyro	Pyro metallurgical process
Hydro	Hydro metallurgical process
Od	Open dumping
Lf	Landfill disposal
Rd	Resale to downstream manufacture
Rc	Recycled
Ru	Reused
Er	Energy recovery
B	Physical process

recovered and recycled, the alleviated mining costs against mining virgin metals will amount to 25.5 $. Recovered and recycled metals through option I will produce 8.3 $ mining cost alleviation. Metals recovered and recycled through options II-a and II-b will offer 24.9 and 12.0 $ mining cost alleviation, respectively. Furthermore, it is estimated that, when the maximum metal contents are recovered and recycled from 100 kg of EoL LCD TV-sets, the alleviated mining cost will amount to 38.4 $. Metals recovered and recycled through option I will bring 12.5 $ mining cost alleviation, whereas recovered and recycled metals through options II-a and II-b will produce 36.1 and 12.2 $ mining cost alleviation, respectively. Thus, the maximum mining saving cost is offered by option II-a, whereas option I provides the least mining saving cost against mining virgin metals. In addition, the recovery of Sn by the Hydro metallurgical process significantly contributed to increasing mining saving costs in both EoL CRT and LCD TV-sets. This is also the reason why option I and II-b were the less effective approaches compared with option II-a.

EoL EEE management scenarios' assessment

Based on the generated amount by the different types of TV-sets and DFs of the resource availability and its variability, the mining saving costs are calculated corresponding to the three scenarios (Fig. 9). In the case of S1 with logistic and linear curves, the mining saving costs are calculated to be 4.1 and 3.3 billion dollars, respectively, in total during the year 2000–2030. In the case of S2 with logistic curve, the mining saving cost of EoL TV-sets through treatment option I is 0.2 billion dollars and the mining saving cost through treatment option II-a is 4.2 billion dollars. In the case of S3 with logistic curve, the mining saving cost of EoL TV-sets through the treatment option I is 1.5 billion dollars and that through the treatment option II-a is 0.6 billion dollars in 2000–2030. When linear curves are applied to S2 and S3 as penetration curves, the mining saving costs of EoL TV-sets in 2000–2030 through the treatment option I are 0.4 and 1.5 billion dollars, respectively, and those through treatment option II-a are 3.6 and 0.4 billion dollars, respectively.

In summary, the mining cost saving in the scenario where informal treatment processes are converted into formal ones by 2020 or 2030, S1 or S2, is estimated at around 2 billion dollars higher than the scenario where informal processes are not or slowly converted. The results show that the future increase in mining costs may be more alleviated in S2 than in S1. However, if we take the uncertainty of penetration curves into account, S2 with a linear curve and S1 with a logistic curve will reduce nearly the same amounts of future mining costs. On the other hand, damages to RA are substantially different in accordance with the choice of penetration curves, even if the year when informal processes are completely replaced with formal ones, 2030 for S1 or 2020 for S2, is the same. This implies that replacement of informal processes needs to be undertaken as immediately and rapidly as possible and should not be postponed.

In dealing with the environmental impact from the improper treatment of EoL EEE, there may have two possible strategies: either the informal treatment yards must be closed and made illegal or the immature treatment processes implemented in those informal sites must be upgraded. This may be done by various ways such as leading-in developed machinery equipment and government subsidy. Those, the applied manual dismantling practices are mature and the fact that informal sites employ rural residents suggests that the latter is more preferable for the current situation in China.

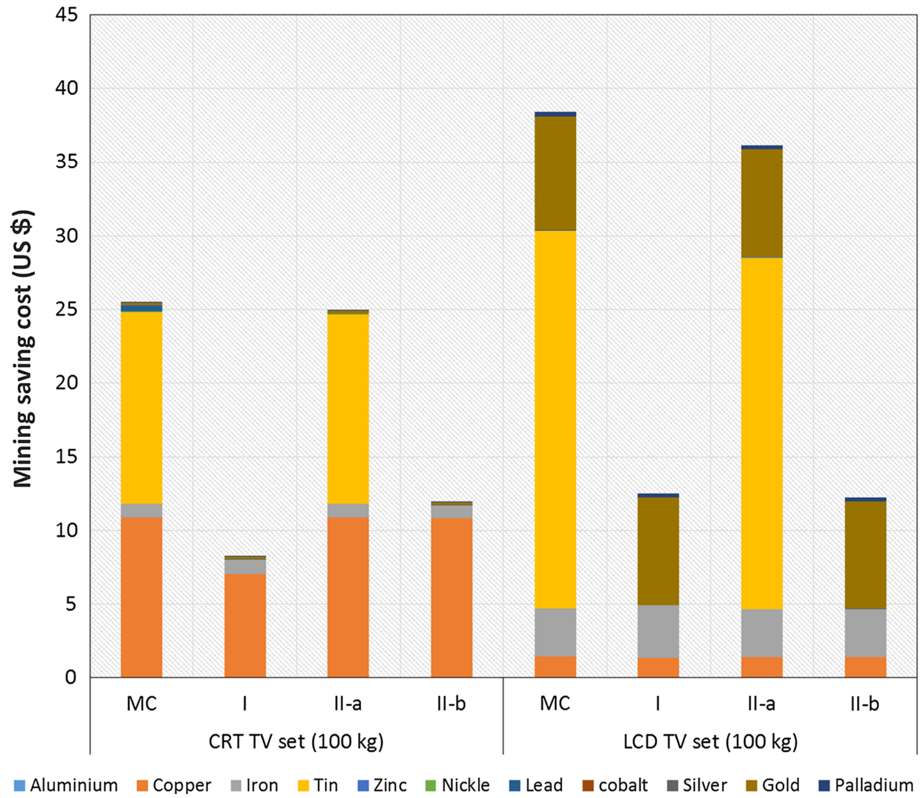


Fig. 8 Mining saving cost from recycling of EoL TV-sets, in three options, in relation to MC

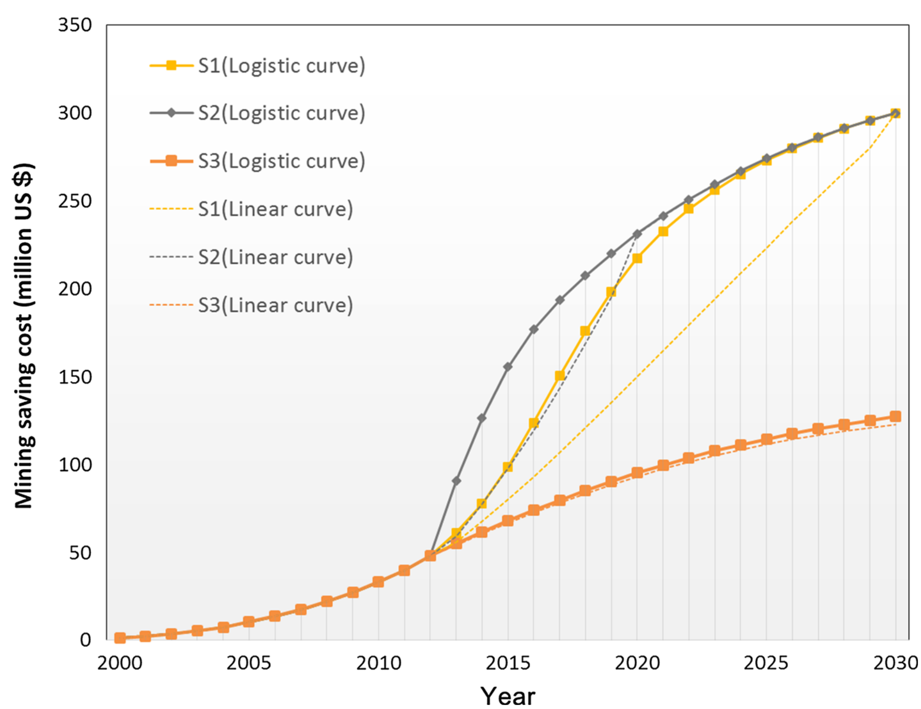


Fig. 9 Comparison of mining saving costs through recycling of EoL TV-sets under the three scenarios in China

Conclusions and recommendations

In the present study, the EoL EEE recycling resource availability potential is assessed on the basis of penetration scenarios for formal and informal recovery and treatment in China. The results provide a quantitative basis for decision makers to develop strategic policies for EoL EEE management, including plans for appropriate recovery and treatment capacity building, to meet the requirements of proper waste treatment and to maximize secondary resource recovery. The metal contents of EoL TV-sets and EoL PCs that have a potentially high negative impact on HH and ED and those that could contribute to alleviating damages to RA are identified. Among them, certain metals such as Pd and Au contained in EoL PCs have a high market value. Therefore, their recovery is economically attractive. The scenario analysis suggests that converting the informal treatment processes into the formal ones by 2020 would significantly alleviate the future mining costs; however, the less mining costs would be alleviated if the conversion was achieved by 2030.

In the present analysis, maximum recovery rates are applied on the various unit processes in three treatment options. Nevertheless, the data in terms of both the recycling efficiency and the recovery rates from the various physical and chemical processes are important to compare the three treatment options. Moreover, the substances' emission ratios vary depending on the substance's characteristics and the treatment techniques. Therefore, it is important to capture the recovery rates and the emission (discharge) ratios of hazardous substances.

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