Urban Mining of E-Waste is Becoming More Cost-Effective Than Virgin Mining

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Supporting Information

ABSTRACT: Stocks of virgin-mined materials utilized in linear economic flows continue to present enormous challenges. E-waste is one of the fastest growing waste streams, and threatens to grow into a global problem of unmanageable proportions. An effective form of management of resource recycling and environmental improvement is available, in the form of extraction and purification of precious metals taken from waste streams, in a process known as urban mining. In this work, we demonstrate utilizing real cost data from e-waste processors in China that ingots of pure copper and gold could be recovered from e-waste streams at costs that are comparable to those encountered in virgin mining of ores. Our results are confined to the cases of copper and gold extracted and processed from e-waste streams made up of recycled TV sets, but these results indicate a trend and potential if applied across a broader range of e-waste sources and metals extracted. If these results can be extended to other metals and countries, they promise to have positive impact on waste disposal and mining activities globally, as the circular economy comes to displace linear economic pathways.

INTRODUCTION

Growth in accumulated stocks of virgin-mined materials continues to present the world with an enormous problem, calling for radical socioeconomic solutions.1,2 E-waste is one of the fastest growing waste stream globally.3,4 More than 40 million metric tons of e-waste—from TV sets to computers to mobile phones as well as household goods like microwave ovens, refrigerators and washing machines—are generated each year.5 This is projected to grow to 50 million tons by 2020. Disposing of e-waste is problematic, since shredding, incineration, especially open burning in an informal operation, poses a risk of releasing many of the toxic components contained in electrical and electronic goods, and secondary pollutants, such as dioxin, mercury, or lead.6−8 Additionally, reuse of components and products is feasible but not desirable owing to the economic and cultural factors.9,10 Recycling whole products or components is also not feasible, since they can be damaged in the process of disposal and are quickly outdated because the pace of technological advancement in the electronics industries is so rapid. One attractive avenue therefore is to recover valuable metals from the e-waste streams, such as copper and gold, in what is called “urban mining”.11−14 The challenge is to develop processes that dismantle the waste products (demanufacturing) and then utilize physical and chemical methods to isolate and purify the metals involved, in a way that makes environmental and economic sense.15 Copper and gold are two of the significant-used metals in high-technology industry.16 In electronics goods alone, demand for utilization of these metals accounts for about 30% and 12% of their total consumption in the whole society, respectively.17,18 From an economic perspective, the total economic share of copper and gold accounts for over 50% among all resources in e-waste so that the two metals remain the leading.19,20 Their extraction through urban mining promises to play an increasingly important role in maintaining the sustainability of the wider IT and electronics industries.21

Previous studies have focused on identifying the valuable materials locked in e-waste streams, the technical means available for extracting (and purifying) them,22 and the degree of recyclability via urban mining.14,23,24 The economic benefits from urban mining—which is what ultimately drives the process—has not been explored to the same extent, so far (with some exceptions in a simply economic analysis25−27). There is still a gap in the literature for studies using more real and dynamic data to demonstrate why urban mining potentially

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makes more economic sense than virgin mining, i.e. extraction of metals from their natural setting in ores.

China is anticipated to generate just over 15 million tons of e-waste in 2020 and 28.4 million tons by 2030, making it a larger generator of e-waste than the U.S. or the EU. On the other hand, China is also now an emerging leading contributor to the urban mining of e-waste, given the potentially high levels of recyclability of e-waste streams and the favorable policies adopted by governments in China at national and provincial levels. These policies are designed to promote collection and extraction of valuable materials from the resultant e-waste streams. Thus, we choose China’s adventure as an example to uncover the economic performance of e-waste recycling.

Among urban mining, China’s adventure in e-waste recycling has attracted global concern since 2000 with the notorious environmental incidents such as Guiyu town as electronic graveyard of the world. Currently, the formal recycler in China pays the fees for labor, energy, material, transportation, residue disposal, equipment, and building. The recycler can obtain the benefit from selling the recovered materials, components selling, and governmental fund for e-waste recycling. In this study, we start with the real costs paid by Chinese e-waste recyclers for their raw material in the form of discarded and collected e-waste: CRTs TV sets. Based on the framework outlined in SI Figure S1, this study is devoted to demonstrating that there is great potential in recycling metals from e-waste through these urban mining processes, and that this provides the ultimate solution to deal with the mounting quantities of e-waste anticipated in the future.

■ MATERIALS AND METHODS

Data on Urban Mining and Virgin Mining. Many urban mining practices have been developed for e-waste recycling from industrial nations to developing countries. The monitor screen and printed circuit boards (PCBs) are the basic components among e-waste, and their recycling can be used to demonstrate the entire process of urban mining for e-waste. We collected the detailed data of urban mining cost for CRT monitor and PCBs, which are the most fundamental parts of e-waste streams. Virgin mining costs for copper, lead, steel, aluminum, gold, and silver were gathered, emphasizing their ranges of costs encountered (see SI Table S1 and Text S1).

The detailed recycling costs for eight recyclers from 2011 to 2015 (based on recycling of one CRT TV) was collected (SI Table S3), indicating that evolution of recycling process can basically impose the recycling cost (SI Tables S4 and S5).

Materials and Methods. Large Sampling Analysis. We first calculate costs for extracting a mix of metals from e-waste stream flows. A large sampling analysis was employed for the practical recycling operation (SI Table S6). Average weight of each CRT TV is about 13.83 kg. So based on resources content of CRT TV (SI Table S7), one typical CRT TV contains 0.4149 kg copper, 0.2766 kg aluminum, 1.383 kg iron, 0.5532 kg lead, 7.3299 kg panel glass, 3.1809 kg plastic, 0.692 g gold, and 0.6901 kg other substances (SI Text S2).

Analytic Hierarchy Process. Urban mining costs are calibrated with difficulty of recycling or recyclability. Previous studies indicate resources in e-waste significantly differ in recyclability. Thus, urban mining costs vary for different resources in e-waste. To determine the cost share of a single resource mining (e.g., copper or gold) of total recycling, we utilize the Analytic Hierarchy Process method to calculate respective shares, as outlined in SI Text S4 and Tables S8–S10.

Learning Curve. In economic science, Theodore Paul Wright described the effect of learning on production costs in the aircraft industry and proposed a mathematical model of the learning curve. A power Law can be employed to describe the learning curve. It is similar in appearance to an exponential decay function, and is almost always used for a decreasing performance metric, such as cost. In this study, we will use learning curve to validate the evolution of urban mining cost in recent years.

Urban Mining Cost for One-kg Ingot Metal. We then calculate the estimated cost of producing a one-kg ingot of pure material, and utilize copper and gold as the outstanding cases for urban mining of e-waste owing to their high recycling potential. We demonstrate that purified copper and gold from e-waste has an estimated cost considerably lower than the world price of copper and gold on commodity markets, and moreover this estimated cost is falling—as would be expected in
a learning (or experience) curve that is characteristic of manufactured (in this case demanufactured) products.

Here, treatment charge is defined as the net fee (total cost of urban mining minus the governmental subsidy) paid by recycler. Thus, the urban mining cost for one-kg ingot metal can be determined by eq 1.

\[
T = \frac{C \times s}{Y}
\]

where \(T\) is the treatment charge cost for one-kg ingot metal (US$/kg), \(C\) is the total treatment charge cost of urban mining (US$), \(s\) is a certain metal’s share or weight of total treatment charge cost (%), and \(Y\) is the yield of a certain metal from urban mining (kg).

**RESULTS AND DISCUSSION**

**Formal E-Waste Recycling: Performance of Resource and Economy.** Worldwide, e-waste recycling has been booming from the EU, the U.S. and Japan to China since 2000s. Significant economic revenues have been generated from the recovery of 14 types of e-waste (e.g., CRT TVs, LCD TVs, LED TVs, CRT monitors, LCD monitors, LED monitors, LCD notebooks, LED notebooks, cell phones, smart phones, PV panels, HDDs, SSDs, and tablets) in Europe. The quantities of e-waste involved are significant to measure the performance of resource recovery and recycling economy.

As shown in Figure 1A, the e-waste stream in China is dominated by CRTs from TV sets, which were accumulated by businesses and households but released to the recycling market after passage of the new regulations. Meanwhile, other white goods (e.g., washing machine, refrigerator, and air conditioner) in China are starting to be recycled with growing levels of collection, labor, energy, material, transportation, residue disposal, and capital costs of equipment and buildings. Recyclers can generate revenues from three sources: from selling recovered materials; from selling recovered components, and from the government subsidy or funds. Eight recyclers which operated from 2011 to 2015 were chosen to provide representative insight into the evolution of urban mining costs, as shown in Table 1. The last column indicates that Heilongjiang’s costs net of government subsidy came to US$3.95 in 2015 for each CRT unit recycled.

**The Total Economics of Urban Mining Versus Virgin Mining.** Both most natural ores and urban mines (i.e., e-waste) are associated minerals. According to SI Table S1, treatment charge or total cost of urban mining (one-ton e-waste recycling) and virgin mining (one-ton metal yield) are determined in Table 2. Basically, cost of metal mining can be divided two types as total cost and cash cost. The former is consisted of cash cost, the expense of running a company, buying and repairing equipment. In this study, we use the total cost to uncover the economic performance. If virgin mining generates 54 kg copper, 60 kg lead, 80 kg steel, 45 kg aluminum, 0.150 kg gold, and 0.090 kg silver as CRT recycling, the total cost will be US$3.95 (16.95 – 13 = 3.95) for recycling of one-unit CRT TV.
recycling, the total cost will be 10,060 US$/ton with a range of 6,850–13,930 (Figure 2). In light of the same yield, the cost of virgin mining will evenly be around 13-fold and 7 fold of cost for CRT recycling and PCBs recycling, respectively. Therefore, the total economics of urban mining for a basket of metals emerge as superior to those of virgin mining.

When the total cost of extracting the basket of metals (with the same yields as CRT recycling) from virgin ores is US$5,990, this figure is dominated (US$5,490, 92%) by the cost of mining the gold, which can be validated by the previous studies.\textsuperscript{25,26} In all other cases, the cost of virgin mining is cheaper than recycling treatment. Accordingly, the cost of mining the gold is significantly predominant in total urban mining cost of e-waste. Meanwhile, the cost of one single metal recycling should be measured using the weighted cost of this metal in urban mining, which will be discussed in detail in the next section.

So our overall conclusion is that e-waste can be treated through demanufacturing, separation and physical reprocessing to yield economic quantities of pure metals like copper and gold, at an estimated cost that is considerably below the observed range (4,099–13,930 US$/ton) of world market prices, even when qualifications regarding the costs of disposal of residue and ignoring the impact of government subsidies paid per unit of CRT TV recycled are taken into account. This viewpoint can be also validated while identifying the profitability of waste PCBs recycling with Germany and United Kingdom as reference nations.\textsuperscript{26,27} Comparing to these works, we have demonstrated the evolution of full costs in e-waste recycling. And besides, comparing to virgin mining, urban mining can not only provide the considerable resource, but also contribute to environmental conditioning (e.g., detoxification of hazardous materials) and positive social impacts (e.g., gainful employment).\textsuperscript{39}

\textbf{The Economics of Urban Mining Versus Virgin Mining for Single Metal.} Now the most salient feature of e-waste, that distinguishes it from all other forms of waste, is that its constituents are all products of manufacturing, and so demanufacturing processes for recycling and recovery are available to deal with the waste stream.\textsuperscript{42} The product attribute of e-waste also means that costs are dependent on the size of the market, which is expanding. These costs can be expected to fall in line with the familiar learning curve that accompanies all demanufacturing activities (SI Figure S3).

While market of copper and gold is provided mainly by virgin mining, the commodity price or value not only reflect supply and demand and market considerations, but indicate the cost of virgin mining conditioned by the profits of the mining company. The core of our contribution is Figure 3A which shows costs of urban mined copper reducing year by year, to reach levels well below the world market price, and Figure 3B which shows the same phenomenon for gold, with even greater range (27,000–52,000 US$/kg) of gap between urban mining cost (1,591–8,438 US$/kg) and the market price (36,000–55,000 US$/kg).

We emphasize that these are the costs as computed by ourselves, and we now proceed to demonstrate their validity. Taking copper as the key metal, our basic finding is that cost of recycling and retrieving metals from each unit of CRT TV reduced from a mean of US$6.70 per kg in 2010 to US$1.70 by 2015—as against the world market prices in 2015 of US$6.00

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Comparison of total integrated treatment charge for urban mining and virgin mining for same metals yield. Note: Scenario 1 with equivalent yield as CRT recycling, and scenario 2 with equivalent yield as PCBs recycling. Dash area indicates the range of value.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Costs of copper (A) and gold (B) recovered from CRT TV (urban mined) versus world commodity prices. Data source: Authors’ calculations, based on data available from actual operations in eight Chinese recyclers from 2011 to 2015 (see SI Table S14).}
\end{figure}
per kg. We derive this estimated cost of US$1.70 for 1 kg copper in 2015 as follows. We start with a real cost, namely the fee paid by a Chinese recycler for one recycled CRT (derived from one TV set). For the recycler Heilongjiang, for example, the recycling fee paid in 2015 was US$3.95 per unit (net of government subsidy paid per unit recycled). As shown in Table 1 the costs of recycling one CRT TV unit have been reducing, and illustrating the learning curve associated with this demanufacturing operation.

Now standard estimates of costs of metals extracted from e-waste are normally performed and estimated for an aggregate output of a mix of metals. In Table 1 we see that there is an estimate of the total costs for an aggregate of metals, in fact a cost estimated at US$3.95 for the aggregate characterized as recycling many valuable materials, that is, 0.39 kg copper, 0.28 kg aluminum, and 0.66 g gold. We wish to go beyond this, to demonstrate an estimate of costs for the individual metals—starting with copper. We can utilize two sources of data, namely the share of copper in the total cost of producing urban mined metal, and the yield of the CRT in terms of the output from the recycler.

First we have the result that the share of copper in the total cost is 16.8%, as shown in the last column in SI Table S10), determined by fully considering e-waste recyclability and the technical process4,23 (see SI Text S4). Thus, the cost to be allocated to copper is the sum of the costs (US$3.95) times 16.8%, or ~US$0.66. This is the cost of the yielded copper, which is an amount estimated to be 0.39 kg—so the cost for a one-kg ingot of copper would be (US$3.95 × 16.8%)/0.39, which is US$1.70 per kg reclaimed copper.

The yields for various metals are shown in SI Tables S7 and S12 as follows: 0.39 kg copper, 1.38 kg iron, 0.28 kg aluminum and 0.66 g of gold, plus 0.82 kg residue. Again we may note from SI Table S5 that the quantity of residue diminishes each year, indicating the existence of a learning curve as yields improve (see SI Figure S5). Thus, we obtain an estimate of the cost of a one-kg ingot of copper secured by urban mining of e-waste as (US$3.95/0.39) × 16.8% = US$1.70 in 2015. We emphasize that this is a realistic estimate of cost that starts with copper. We can utilize two sources of data, namely the share of copper in the total cost of producing urban mined metal, and the yield of the CRT in terms of the output from the recycler.

We follow a comparable procedure to estimate the cost of a one-kg ingot of gold extracted and purified from e-waste, where the results are displayed as 1.591–8.438 US$/kg in Figure 3B. It may be seen that the cost of urban mined gold from CRT TV (i.e., e-waste) has been far lower than the world commodity price each year, and is falling as per the learning curve associated with the processes of demanufacturing involved. By 2015 the estimated cost of urban mined gold had fallen to US $1,591 per kg in 2015, compared with the world commodity price of just under US$4,000 in the same year.

Three qualifications are immediately in order. First, we have included the government subsidy of US$13 for the output of metals aggregated from one unit of CRT TV. Without this subsidy (which drives the economics) the mining of metals from e-waste would not be so attractive. In SI Table S15 we show how the costs of urban mined copper and gold would compare with world commodity prices if the subsidy is ignored. We can see that costs of extracting copper are not significantly attractive (although still below the world price for each year from 2010 to 2015), while costs for extracting gold are well below the world commodity price. Thus, our calculations reveal that the Chinese government subsidy makes sense at this point in the evolution of urban e-waste mining. Second, we have not included the costs of disposing of the residue left at the end of the reprocessing, which have been rising as the force of government regulation for the industry has been intensifying. We estimate these costs of disposing of residues to be around US$300 per ton of residue in 2005 rising to US$1,100 per ton of residue in 2015 owing to increasing strictness in law enforcement and growth of the electronics industry.33 This would translate to somewhat less than US$0.66 to be added per kg of reclaimed copper (SI Table S16). This does not therefore have a great impact on the estimated costs, which remain below those of virgin mined copper on world commodity markets.

The future for an industrial economy based on the products manufactured from flows of resources lies in becoming less dependent on virgin extraction (which cannot continue in any sustainable manner) than on circulation of materials extracted from recycled products.44,45 This is one important aspect of what is known as the circular economy which deserves more research as an emerging area of policy and business analysis, especially in China.46,47 Our results help to explain why there is an emerging boom in mining of pure metals needed in e-waste (e.g., copper and gold needed for CRTs, plasma TVs, and circuit boards). Our results also demonstrate why government subsidies are necessary to make extraction of valuable metals from e-waste streams economically, and by doing so, ease the otherwise unmanageable social costs associated with increasing stockpiles of discarded electronic goods.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b04909.

Figures S1–S5; Texts S1–S5; and Tables S1–S16 (PDF)

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Notes
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