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Measuring the recyclability of e-waste: an innovative method and its implications

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ABSTRACT

The viability of closed-loop recycling of electronics can sustain the future development of the flourishing electronics industry. Identification for the recyclability of e-waste (or WEEE) plays an enhanced role in process designing and policy making. However, precise measurements of recyclability, subjected to resource reclamation and environmental protection analysis, have not yet been well recognized. This study defines the rules of grade determination for various materials in any given WEEE, then combines these rules with the Statistical Entropy function, to develop an innovative model to measure the recyclability, emphasizing the product design stage, in order to significantly promote qualitative to quantitative eco-design. Using this model, not only e-waste recycling can be partitioned into three levels of difficulty, but also the measurement method can be employed to divide the responsibility for electronics recycling between producer and recycler.

1. Introduction

Electronics has become the largest and the most flourishing industry in the world, and is recognized to be the greatest "Value Adding" and high-technology industry, which is rapidly changing the economic and social landscape (Li et al., 2015b; Lu et al., 2015). At the end-of-life (EoL) stage of electronics, however, a copious derived e-waste (or WEEE) has become a global concern owing to its potential damage to the environment and store of critical resources (Chen et al., 2016; Hartard and Liebert, 2015). The annual amount of global WEEE generation has surpassed 40 million tonnes (Baldé et al., 2015), of which 9 million tonnes was supplied by China (Zeng et al., 2016). Although many recycling facilities have been established throughout the world, they achieved only 13% formal recycling rate owing to inadequate collection and poor technical capacity (Jiang et al., 2012). As a global society we are still far from a closed-loop materials system, more efficient recycling is crucial to enable the recovery of critical materials and solve the global e-waste problem (Li et al., 2015a).

Basically, efficient recycling for electronics is dependent on sophisticated technology and processes (Wang and Xu, 2015; Zeng et al., 2015b). A theoretical guide to recycling process is of necessity to utilize the past experience and to cope with emerging electronics. Additionally, eco-design (or design for environment) has been much emphasized by producers, consumers, and recyclers (Stevels et al., 2013). But extensive analysis of the eco-design of products by many producers has determined that such design is currently focused only at the qualitative level (Li et al., 2015b). Quantification of eco-design is therefore also needed for producers to ensure that their new electronics are indeed superior to the old ones.

E-waste recycling is much concerned by producers or manufacturers under the extended producer responsibility (EPR) policy (Gupt and Sahay, 2015; Wang et al., 2014)—in most cases, via paying the recycling cost, which is strongly related to the economic value of recycled products and the overall processing cost. The former is easily obtained from the composition of WEEE. The economic value of materials contained in WEEE depends not only on the concentration of recyclable materials contained in the products, but also upon the chemical property (*e.g.* valence) of the materials (Cucchiella et al., 2015). Thus, the overall expenses of WEEE treatment are strongly related to the full recycling process, including physical treatment (*e.g.* manual dismantling, mechanical treatment, or thermal treatment) and chemical recovery (*e.g.* hydrometallurgy and pyrometallurgy) (Le et al., 2014; Zeng et al., 2014, 2015a).

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The term 'recycling potential' has been defined from an economic perspective, satisfying the requirement that potential e-waste recycling revenues exceed the costs of collection, transportation, and processing (Bartl, 2014; Dahmus and Gutowski, 2007; Graedel, 2011b). Owing to economic fluctuation and rapid technological innovation, however, recycling potential does not take into account the entire processing cost and thus cannot always reflect the nature of the recycling technology. Here we define recyclability as the theoretical probability of an item's actually being recycled, taking into account the recycling difficulty for metals, plastics and glass in physical treatment and chemical recovery (Fig. S1 of Supplementary content (SC)) (Villalba et al., 2002, 2004). The definitions and properties of recycling potential, recyclability, and recycling difficulty have been addressed in SC Text1. Therefore, the net recycling cost of WEEE depends upon its recyclability, not its recycling potential, which is only relevant to the concentration of recoverable materials within it. A comprehensive theoretical guide to recycling processes, quantitative eco-design, and recycling responsibility is quite essential to determine the authentic recyclability of e-waste. In this study, we create innovative mathematical models, based on the physical and chemical characteristics of materials contained in e-waste, to measure the recyclability and recycling difficulty of various types of electronics. We then analyze the differences among the various e-waste types and recycling scenarios, and endeavor to determine how each of them might contribute to the development of e-waste regulations, electronics eco-design, and recycling responsibility.

2. Methods

2.1. Basic assumptions and factors analysis

The attributes of a product can be ascribed to the quality and quantity of its ingredients (or materials) (Zeng et al., 2004). The terms "substance," "goods (or product)," and "material" in material flow analysis can be defined as in chemical science: a substance is any chemical element or compound composed of uniform units, characterized by a unique and identical constitution and thus homogeneous; goods are defined as economic entities of matter with a positive or negative economic value, and made up of one or several substances; and material is composed of or can be fabricated from elements, constituents, or substances (Allesch and Brunner, 2015; Brunner and Rechberger, 2004). In the result, WEEE can be regarded as goods, unitary metal (iron or copper) or plastic as substances, and mixed metals or plastics as materials.

Aside from external factors such as available technology and economic feasibility, the recyclability of electronics is in essence dependent upon the types and quantities of its elements and their grades. For instance, metals' recyclability in urban mining is also attributed to metals form: metals used in pure form are judged to be relatively easy to recycle (Graedel, 2011a). The types and quantities refer to the concentrations of various valuable materials (*e.g.* metals and plastics) and other materials; for instance, e-waste recycling should consider not only the metals (as elemental or combined substances), plastics and glass, but also some less valuable materials such as resin. The grade is to measure the quality of various materials, which varies depending on the levels of natural minerals in a given substance.

2.2. The statistical entropy function

Entropy is a state function that is often erroneously referred to as the 'state of disorder' of a system. Qualitatively, entropy is simply a measure how much the energy of atoms and molecules become more spread out in a process and can be defined in terms of statistical probabilities of a system or in terms of the other thermodynamic quantities. The concentration of all materials in electronics has been substantially evaluated by Shannon's Statistical Entropy function of Information Theory (Rechberger and Brunner, 2001), which can measure the loss or gain of information about a system or the variance of a probability distribution. This theory has been successfully adopted in material flow assessment through quantifying the power of a system to concentrate or dilute substances (Yue and Lu, 2008). The statistical entropy H of a finite probability distribution is expressed by the following equations (Cover and Thomas, 2012):

$$H = -\sum_{i=1}^{n} (Pi \cdot \log_2 Pi) \tag{1}$$

$$\sum_{i=1}^{n} Pi = 1 \tag{2}$$

where P_i is the probability that event i happens, replacing the concentration of i material; n is the total number of materials in a given WEEE; and H is the entropy (here its unit is a bit in Information Theory).

2.3. Determination method of grading materials

Here we define that the initial phase of WEEE recycling is the EoL electronics, and the targeted phase is the final recovered materials. Actually, the final recovered materials are depended upon the utilization purpose, and the recycling & recovery process. But in most cases, the final recovered materials from e-waste are pure metals or plastics using physical treatment and hydrometallurgical process. Thus, the targeted phase of WEEE recycling can be defined as pure metals or plastics.

The grade of the materials within WEEE is the most difficult to determine, but it can be revealed by quantifying the divergence between the initial phase and the targeted phase as recovered product. Basically, two situations can be identified to address this issue. First, in the case of some mixed-material goods, the grade of one material is regarded as the concentration of the goods. For instance, metallic powder containing copper and nonmetals could be commonly obtained from the mechanical and electrostatic separation of e-waste (Zeng et al., 2012); thus, the grade of copper (zero-valence state) in the goods can be determined with the content of copper. The grade of alloy, in particular, will be defined as the concentration of a certain metal based on the assumption that the target recovery phase is pure metal (zero-valence state). Secondly, with respect to some metals in a chemically combined substance, the grade is subject to the combined price. If the targeted phase is pure copper, for instance, the grade of CuO (two-valence state) is lower than the one of Cu_2O (one-valence state). Hence, the grade of goods can be defined as the sum of the grades of all its materials, as shown in Equation (3):

$$D = \sum_{i=1}^{m} Di = \begin{cases} \sum_{i=1}^{m} Pi & \text{(physically mixed goods)} \\ \sum_{i=1}^{m} [1-(ji-1)/N]i & \text{(chemically combined goods)} \end{cases} \tag{3}$$

where D_i is the grade of material i; m is the number of materials in a given WEEE ($m \leq n$); j is the ranking of valence from low to high; N is the total number of all the valences of a given element; and D is the total grade of the WEEE (here its unit is dimensionless).

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