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Life cycle assessment of electronic waste treatment

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Life cycle assessment was conducted to estimate the environmental impact of electronic waste (e-waste) treatment. E-waste recycling with an end-life disposal scenario is environmentally beneficial because of the low environmental burden generated from human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity categories. Landfill and incineration technologies have a lower and higher environmental burden than the e-waste recycling with an end-life disposal scenario, respectively. The key factors in reducing the overall environmental impact of e-waste recycling are optimizing energy consumption efficiency, reducing wastewater and solid waste effluent, increasing proper e-waste treatment amount, avoiding e-waste disposal to landfill and incineration sites, and clearly defining the duties of all stakeholders (e.g., manufacturers, retailers, recycling companies, and consumers).

1. Introduction

Electronic waste (e-waste) refers to waste generated from discarded electrical or electronic devices (e.g., cell phones, computers, TV, printers). Given the vast technological advancement and economic development in many countries in recent years, the volume of e-waste produced has significantly increased (Qu et al., 2013; Robinson, 2009). The current global production of e-waste is around 25 million tons per year (Robinson, 2009), with the greatest amount of e-waste imported in China (Chi et al., 2014). However, compared with e-waste recycling in developed countries, that in China suffers from a high occurrence of environmental pollution and low energy efficiency. One of the most important mineral resources, e-waste is traditionally recovered in China by workers with the use of open flames or hot plates as a convenient way to remove electronic components (Allsopp et al., 2006). The improper handling of e-waste releases heavy metals (e.g., lead, cadmium, mercury, and beryllium) and hazardous chemicals (e.g., dioxins, furans, polychlorinated biphenyl) that seriously deteriorate the atmosphere, water, and soil quality (Li et al., 2014; Xu et al., 2014) and thus affect human health (Liu et al., 2009). The potential environmental impacts generated by e-waste recycling are complex and involve multi-factorial participation (e.g., process, activity, and substances). In this regard, a systematic consideration of emission inventories and the environmental potential impacts caused by e-waste recycling is highly needed.

Life cycle assessment (LCA) is a systematic approach to assess and quantify the environmental performance associated with all stages of a product creation, processes, and activities (ISO 14040, 2006). LCA can simultaneously, systematically, and effectively evaluate and identify environmental inventory, impact, key factors, decisions, optimization, and improvement opportunities associated with all stages of system boundary. Several studies have analyzed the environmental impact of e-waste treatment on the environment via LCA (Song et al., 2012; Niu et al., 2012). Song et al. (2012) investigated e-waste treatment by using emergy analysis combined with the LCA method for a trial project in Macau. Their results showed that recovery of metals, glass, and plastic from e-waste can generate environmental benefits. Niu et al. (2012) compared three cathode ray tube (CRT) display treatment scenarios (i.e., incineration, manually dismantling, and mechanically dismantling) via LCA by using literature review. Their results showed that the incineration of CRT displays has the greatest impact, followed by mechanical dismantling. Despite their scientific contributions, the aforementioned studies are unclear as to whether direct air, water, and soil emissions from the industry site of e-waste recycling are included in the calculation of results. Inventory databases are also variable in terms of regionalization,

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geography, and uncertainties involved. However, in the aforementioned studies, no regionalized database was selected to determine the environmental effects of e-waste in China. Most data were collected from European database (Ecoinvent centre, 2010). Therefore, accurate results for Chinese case studies are difficult to obtain. The quantification and communication of uncertainties related to LCA results are also vital for their correct interpretation and use. However, most LCA experts, including the authors of the aforementioned studies, still conduct LCA without considering uncertainties. The environmental impact generated from informal recycling processes should also be quantified because substantial e-waste in China is recycled by individual workshops (Lin and Liu, 2012). In this regard, the current study aims to address the aforementioned needs, identify the key factors to improve the processes in the Chinese e-waste recycling industry, characterize and compare two e-waste recycling technologies commonly applied in China, and introduce a Chinese e-waste recycling database.

2. Scope definition

2.1. Functional unit

In this study, the management of 1 ton of e-waste (i.e., computer and television) is selected as the functional unit to provide a quantified reference for all other related inputs and outputs. All air, water, and soil emissions, raw materials and energy consumption, and waste disposal are based to this functional unit.

2.2. System boundary

System boundaries were set by application of a gate-to-gate approach. Two scenarios commonly used in China were considered in this study, namely, e-waste treatment with end-life disposal (ET-D) and e-waste treatment without end-life disposal (ET-ND). Fig. 1a presents the system boundary and mass flow for the ET-D scenario. The ET-ND scenario is simpler than the ET-D scenario because the pollutant control system is commonly excluded in the ET-ND scenario in many individual workshops (Fig. 1b). The ET-D scenario involves raw materials and energy production; road transportation of raw materials to the e-waste treatment site; direct air, water, and soil emissions during e-waste treatment processes (i.e., classification, disassembly, crush, electrodialysis, and metal refining); and waste disposal (i.e., on-site wastewater and air pollution treatment, landfill and leachates treatment, incineration). To simplify the LCA analysis of the ET-D and ET-ND scenarios, the common process of e-waste collection to the e-waste treatment site is excluded. The infrastructure (i.e., construction and equipment) process is also excluded because of the lack of information from selected e-waste treatment sites. Moreover, infrastructure provides a minimal overall contribution to the potential environmental impact (Ecoinvent centre, 2010).

2.3. Life cycle impact assessment methodology

Life cycle impact assessment (LCIA) results were calculated at midpoint level by using the ReCiPe method (Goedkoop et al., 2009) because the fate exposure of this model is consistent with multimedia modeling. This method is also the most recent indicator approach available in LCA analysis. It considers a broad set of 18 midpoint impact categories (i.e., human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine eutrophication, marine ecotoxicity, urban land occupation, natural land transformation, agricultural land occupation, water depletion, metal depletion, and fossil depletion). Normalization, which is determined by the ratio of the impact per unit of emission divided by the per capita world impact for the year 2000 (Wegener Sleeswijk et al., 2008), was applied in this study to compare midpoint impacts and analyze the respective share of each midpoint impact to the overall impact. The complete characterization factors and detailed methodology for ReCiPe are available on the website of Institute of Environmental Science in Leiden University of Nederland (http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/recipe.html).

To determine the level of confidence in the assertion that ET-D is more environmentally friendly than ET-ND, uncertainty analysis is performed via Monte-Carlo analysis by using Simapro 8.0. The geometric variation coefficient (GSD^2) defined the 2.5th and 97.5th percentiles, namely, the 95% confidence interval of a probability distribution near the median μ. For each unit process, the GSD^2 for all LCI parameters is defined by Eq. (1) (Ecoinvent centre, 2010).

$$GSD^2 = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}} \quad (1)$$

where U_b is the basic uncertainty factor, whereas U_1, U_2, U_3, U_4, U_5, and U_6, are the uncertainty factor for reliability, completeness, temporal correlation, geographic correlation, other technological correlation, and sample size, respectively The detailed methodology for Monte-Carlo analysis using Simapro software is available in the Ecoinvent report (Ecoinvent centre, 2010). Additionally, the contribution of individual parameters in the life cycle of both scenarios is identified by Eq. (2) (Hong et al., 2010a).

$$GSD_O^2 = \exp\left[S_{I_1}^2(\ln GSD_{I_1}^2)^2 + S_{I_2}^2(\ln GSD_{I_2}^2)^2 + \cdots S_{I_n}^2(\ln GSD_{I_n}^2)^2\right]^{1/2} \quad (2)$$

where GSD_O^2, S_i, and ${GSD_i}^2$ are the overall coefficient of variation in the final result, the model sensitivity to each input parameter (i), and its coefficient of variation of individual inputs, respectively.

2.4. Data sources

Operation data (i.e., energy, chemicals, raw material, water, wastewater, solid waste, and product) and direct water and air emissions (i.e., before and after pollutant treatment) from an e-waste recycling site in Tianjin, China were collected to generate a life cycle inventory for e-waste treatment (Table 1). The annual capacity for e-waste treatment in this site, which is a professional dismantling enterprise in northern China, is around 24 kt in 2012. For the ET-ND scenario, the company monitoring data of the Tianjin e-waste recycling site related to the direct air and water emissions from e-waste classification, disassembly, crushing, electrodialysis, and metal refining process before pollutant treatment were used to generate water and air emissions. Furthermore, data from five Guiyu e-waste dumpsite samples were aggregated to generate the average direct soil emissions for the ET-ND scenario (Brigden et al., 2005). Guiyu is a town located in Guangdong, China and is one of the largest e-waste sites in the world. This town has been extensively working in the e-waste processing business by using primitive and hazardous methods (Sthiannopkao and Wong, 2013; Brigden et al., 2005). It therefore represents a typical situation for the ET-ND scenario. In addition, 2009 onsite data-based life cycle inventory (LCI) on coal-based electricity generation (Cui et al., 2012), theoretical LCI calculation of road transport data (Chen et al., 2014), and 2007 onsite data-based LCI on solid waste landfill and incineration (Hong et al., 2010b) in China were used in this study. Relevant background data from Europe (Ecoinvent centre, 2010), including those on chemical production, were also collected because of the limited information on sites.