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Comparative environmental life cycle assessment of waste mobile phone recycling in China

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The number of waste mobile phones (WMPs) has increased dramatically in recent years. A complete recycling network is being developed in China, and the WMP recycling process will need to be industrialized. WMPs are valuable, but the potential environmental pressures resulting from recycling processes are currently not well understood. Three recycling scenarios were constructed to represent different current WMP treatment methods, and life-cycle assessments of the environmental impacts of the scenarios were performed. All three scenarios offered environmental benefits, but the scale of the benefits decreased in the order scenario 3 > scenario 2 > scenario 1. Recycling printed circuit boards and metals in the lithium batteries, possible because of the modularization process, was most environmentally beneficial. Environmental impacts were divided into 10 subcategories: recycling decreased the impacts of acidification and nitrification, carcinogenic effects, climate change, ecotoxicity, fossil fuel use, inorganic respiratory effects, and mineral effects more than the impacts of the other categories. The industrialization of WMP recycling should be based on a "manual disassembly plus modularized recycling" model (scenario 3). These results will allow decision-makers involved in the disposal of WMPs to improve the efficiency with which resources (including energy) can be recycled from WMPs.

1. Introduction

The first mobile phone for civilian use was invented in 1973 by Martin Cooper, and mobile phones have since become essential parts of daily life and are the most commonly manufactured electronic device (Ongondo and Williams, 2011). The penetration of mobile phones and the speeds at which mobile phones are upgraded have increased in recent years. China has been the largest producer and seller of mobile phones in the world since 2004 (Ministry of Information Industry, 2005). The number of mobile phone users in China reached 1.3×10^9 at the end of 2014 (Fig. 1). The life expectancy of a mobile phone was less than 3 years in 2014 (Yin et al., 2014). As a result, almost 77×10^6 WMPs are produced in China every year; constituting about 25% of the total number of WMPs produced globally (Yu et al., 2010; United Nations Environment Programme, 2010).

Mobile phones contain complicated ranges of components, as is typical of waste electrical and electronic equipment (WEEE). Improper disposal of WMPs can result in serious potential hazards to the environment and to human health (Wong et al., 2007; Osibanjo and Nnorom, 2008; Yadav and Kumar, 2014; Hibbert and Ogunseitan, 2014). Many WMP components, particularly batteries and printed circuit boards (PCBs), contain heavy metals, such as Cd, Cu, Ni, Sb, and Pb, and other persistent biologically accumulative toxic substances that can pollute the air, soil, and water if the WMP is arbitrarily discarded, incinerated, buried, or otherwise disposed of improperly. Many of these environmentally persistent toxic substances can bioaccumulate and biomagnify (Most, 2003; IPMI, 2003).

Some of the metals in WMPs are valuable and can be recycled or reused to decrease environmental pollution and the need for exploitation of new resources. The mean contents and value ratios of metals in a typical mobile phone are listed in Table 1 (Wu et al., 2008; Lindholm, 2003; Tan, 2005). Large amounts of some metals (e.g., Cu) are found in WMPs, but some metals (e.g., Au) are more valuable than others. More than 154 t of Al, 11 t of Ag, 3 t of Au, 1000 t of Cu, and 385 t of Fe could be recovered from WMPs each year assuming that all of the metals in WMPs could be recycled,

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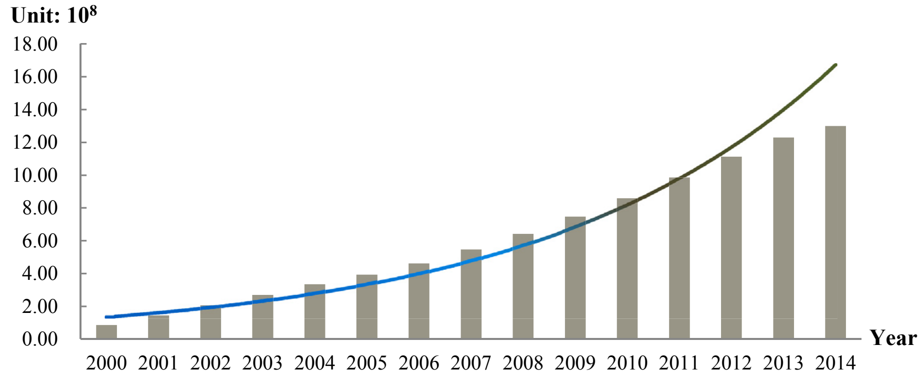

Fig. 1. Numbers of mobile phone users in China between 2000 and 2014. The data were provided by the Chinese Ministry of Industry and Information Technology (Ministry of Information Industry, 2014).

that the mean mass of a mobile phone is 100 g, and that 77×10^6 WMPs are produced each year. Recovery of these metals would clearly be economically beneficial.

Effective processing or use of WMPs is a new challenge. WMP collection and recycling rates in China are low (Yin et al., 2014; Gao, 2012). Li (2015) found that 64% of Chinese users keep their WMPs at home, approximately 20% give their WMPs to relatives and friends, 6% sell their WMPs, 4% throw their WMPs away (into the municipal waste stream), and only 1% pass their WMPs to formal collection agencies without being paid. There are a number of reasons for these figures, including that there are no appropriate WMP recycling systems in China, that it is unclear how WMPs should be recycled, that users are responsible for ensuring that their WMPs are recycled, that the incentive mechanisms for recycling WMPs are not effective, and that the techniques and infrastructure for recycling WMPs are underdeveloped. Consumers often have little awareness of the opportunities and benefits offered by recycling WMPs, worry about divulging private information, do not know where WMPs are collected, or are dissatisfied with the prices paid for WMPs (Gao, 2012; Li, 2015; Yin et al., 2014). However, a recycling network is being developed in China. A series of administrative laws, department regulations, and standards has been issued in recent years. Regulations including “Measures for the Control of Pollution from Electronic Information Products (Chinese RoHS Directive)” in 2006, “Regulation on the Administration of the Recovery and Disposal of Waste Electrical and Electronic Products (Chinese WEEE Directive)” in 2009, and “Special Planning for the ‘Twelfth Five-year’ Waste Recycling Technology Project” in 2012 have been proposed to promote complete recovery of WMP components and to normalize the treatment of WMPs. On 9 February 2015, the latest “Directory of Waste Electrical and Electronic Products Processing” was enacted, which includes WMPs. This inclusion means that WMPs are now part of the management scope of this regulation. A far higher proportion of WMPs will be recovered and recycled in the future than at present, but it is unclear what the environmental footprint of WMP recycling will be in the future. Detailed research into the environmental impacts of WMP treatment processes is required to facilitate avoidance of pollution that could be caused by recycling WMPs.

Table 1
Mean contents and value ratios of metals in a typical mobile phone.

Element	Cu	Fe	Al	Sn	Pb	Ag	Ni	Au	Pd
Content (%)	13	5	2	0.5	0.3	0.14	0.1	0.035	0.02
Value ratio (%)	4.3	0.2	0.3	0.6	0.03	3.9	0.1	78.8	11.8

Sources: Yu et al. 2010; Wu et al., 2008; Lindholm, 2003; Tan, 2005.

Life-cycle assessment (LCA) is an effective environmental assessment tool that can be used to quantify the environmental impacts of the processes used to treat WMPs produced in China (International Organization for Standardization 14040 Series, 2006a and 14044 Series, 2006b). A more detailed life-cycle inventory than is currently available is required for a LCA to be performed for WMPs treated in China. Thus far, little research has been conducted on the characteristics of WMP components and the techniques that are used to recycle WMPs in China. The research efforts that have been made have been parts of studies focused on other electronic waste (e-waste) recycling. LCA has been used in some studies to determine the environmental impacts of certain stages or of certain components and to identify pollution hot-spots; other studies have focused on the entire life cycle of mobile phones (Cai, 2009; Wei, 2005). Those studies demonstrated that the production and disposal of certain mobile phone components, such as PCBs, electronic components, and batteries, have important impacts on the environment, including in terms of acidification and nitrification, climate change, and resources (Yang et al., 2004; Singhal and Nokia Corporation, 2005). It has also been shown that the extraction of raw materials used to produce mobile phones, the use of mobile phones, and the disposal of WMPs have strong impacts on the environment (Ram et al., 1999; Yu et al., 2010; Herrmann and PE International, 2008; Park et al., 2006). However, little research on the environmental impacts of WMP recycling processes has been performed using the LCA method, although some studies of remanufacturing processes, WMP retrievability, and the ecological efficiencies of recycling and retrieving rare metals have been carried out (DeVierno, 2011; Socolof et al., 2006; Huisman, 2003; Skerlos et al., 2003). One reason for this is that more attention is paid to large, heavy, and easy-to-collect WEEE, whereas small WEEE (e.g., WMPs) have not received as much consideration, so collection rates have been low. In addition, little information is available on the properties of WMP components, recycling techniques, or life-cycles, and the data that are available are scattered sporadically in various research publications on WEEE.

We have been making great efforts to develop a recycling network to cope with the huge and increasing numbers of WMPs produced in China. In the present study, we used LCA to evaluate the recycling of discarded WMPs in China. This study is necessary because of the potential damage WMPs can cause and the commercial value of WMP components. Several typical recycling techniques are investigated here because there is no systematic WMP recycling scheme in China. Three recycling scenarios were constructed to allow the environmental impacts of different treatment methods to be assessed. The results will improve our understanding of how WMPs should be treated and allow decision-makers to