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Environmental impacts and benefits of state-of-the-art technologies for E-waste management

Mahdi Ikhlayel

Graduate Program in Sustainability Science-Global Leadership Initiative (GPSS-GLI), Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8563, Japan

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ABSTRACT

This study aims to evaluate the environmental impacts and benefits of state-of-the-art technologies for proper e-waste handling using Jordan as a case study. Life Cycle Assessment (LCA) was employed to evaluate five advanced management systems represent state-of-the-art treatment technologies, including sanitary landfilling; proper recycling of metals, materials, and precious metals (PMs); and incineration of plastic and the hazardous portion of printed circuit boards (PCBs). Six e-waste products that contribute the most to the e-waste in Jordan were included in the assessment of each scenario, which resulted in 30 total cases of e-waste management. The findings indicated that landfills for the entire components of the e-waste stream are the worst option and should be avoided. The most promising e-waste management scenario features integrated e-waste processes based on the concept of Integrated Waste Management (IWM), including recycling materials such as non-PMs and PMs, incinerating plastic and the hazardous content of PCBs using the energy recovered from incineration, and using sanitary landfills of residues. For this scenario, the best environmental performance was obtained for the treatment of mobile phones. Incineration of the portion of hazardous waste using energy recovery is an option that deserves attention. Because scenario implementation depends on more than just the environmental benefits (e.g., economic cost and technical aspects), the study proposes a systematic approach founded on the IWM concept for e-waste management scenario selection.

1. Introduction

1.1. E-waste management and existing studies

E-waste, also known as Waste Electrical and Electronic Equipment (WEEE), is becoming one of the fastest-growing waste streams worldwide. E-waste is a rising global concern due to its alarmingly increasing volume and toxicity. It contains over 1000 substances, many of which are toxic, and creates serious pollution upon disposal (Puckett et al., 2002). It also has detrimental effects on the environment and public health (UNEP, 2007; Herat and Agamuthu, 2012; Song et al., 2014; Baldé et al., 2015).

Examples of hazardous substances include cadmium, chromium, lead, and antimony (Puckett et al., 2002; Agrawal et al., 2004; Ahluwalia and Nema, 2007; Umesi and Onyia, 2008; SEPA, 2011; Kiddee et al., 2013); they require adequate recycling to protect human health and the environment. Valuable metals (e.g., ferrous metals, copper, and aluminum) and precious metals (PMs) (e.g., gold, platinum, palladium, and silver) can be put back into the use chain through proper recycling. An added value is the energy consumption of recovered metals is usually less than for primary production (UNEP, 2013).

Given the rapid growth, a major issue related to e-waste is the improper management of its disposal, which leads to significant environmental impacts (Babbitt et al., 2009; Herat and Agamuthu, 2012), including emissions of toxic substances to water, air, and soil. For instance, informal recycling sectors in developing countries are common, and the recycling methods are usually rudimentary with lax environmental legislation (Tsydenova and Bengtsson, 2011). In some countries like China, e-waste is widely recycled by the informal sector (Chi et al., 2011). Controlled landfilling (sanitary landfilling) is also often lacking in developing countries (Hoornweg and Bhada-Tata, 2012). In developing countries (low-income, lower-middle-income, and middle-income), open dumps account for 12.5%, 48.8%, and 32.4%, respectively, and landfills 58.51%, 11%, and 59%, respectively (Hoornweg and Bhada-Tata, 2012).

The literature presented here aims to review several key studies related to e-waste management. The purpose of this review is to distinguish between this study and previous research, and how the current study fills the gap in the e-waste management literature. Several studies were conducted to address e-waste issues in

E-mail address: mahdi.ikhlayel@ieee.org

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developed and developing countries. For instance, Menikpura et al. (2014) conducted a study to assess the co-benefits of e-waste recycling of washing machines, refrigerators, air conditioners, and televisions in Japan regarding greenhouse gas (GHG) reduction. Bigum et al. (2012) modeled the recovery of aluminum, copper, gold, iron, nickel, palladium, and silver from high-grade e-waste. Their study considered manual sorting, shredding, magnetic sorting, eddy-current sorting, and optical sorting. Studies like Noon et al. (2011) assessed waste from computer monitors in the Seattle metropolitan region and considered several treatment options: reuse, recycling, sanitary landfilling, and hazardous waste landfilling. Socolof et al. (2005) studied 20 environmental impacts of the entire life cycle of cathode ray tubes and liquid crystal displays of computer monitors. Wager et al. (2011) presented results of combined Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) to estimate the environmental effects of the collection, pre-processing, and processing of e-waste in Switzerland. Their study considered e-waste either incinerated in a Municipal Solid Waste (MSW) incineration plant or landfilled.

Tsydenova and Bengtsson (2011) conducted a review study to summarize the existing knowledge of hazardous chemicals associated with e-waste recycling and the End-of-Life (EoL) treatment options for developing and developed countries. Andrae and Andersen (2010) conducted a literature review for key LCA studies on consumer electronics. The focus was on the Global Warming Potential in different life cycles. Song et al. (2012) employed LCA to investigate environmental performances of PCs in Macau, considering the entire life cycle. Song et al. (2013) investigated the environmental impacts of an e-waste treatment enterprise in China for TVs, PCs, air conditioners, refrigerators, and washing machines. Hischier et al. (2005) combined MFA and LCA to assess the environmental impacts of two Swiss take-back and recycling systems. Several studies—including Leung et al. (2006), Estrellan and Iino (2010), Jinhui et al. (2011), and Wu et al. (2015)—estimated emissions from informal recycling.

de Souza et al. (2016) aimed to assess sustainability and prioritize system alternatives for e-waste management in Rio de Janeiro, Brazil. The work primarily focused on Multi-Criteria Decision Analysis (MCDM) using LCA. The study introduced an approach to e-waste management scenario selection based on MCDM. Hong et al. (2015) conducted an LCA study to estimate the environmental impacts of e-waste from computers and TVs by considering two common scenarios in China: e-waste treatment with and without EoL disposal. The second scenario (without EoL disposal) considered e-waste is incinerated.

The existing studies that focused on the EoL phase did not consider treatment and disposal of several appliances individually and as a whole with the current advanced e-waste management technologies. Such technologies include sanitary (controlled) landfill; recycling of materials, metals, and PMs; and incineration. Therefore, this study presents a comprehensive environmental evaluation of the examined appliances in scenarios of state-of-the-art e-waste technologies, as well as the performance of the treatment and disposal of each appliance in each scenario. Further details of the study's approach are explained in Section 1.3.

1.2. Related E-waste management studies about Jordan and the present situation

Jordan was selected as a case study in the Middle East and North Africa (MENA) region because its environmental performance is reportedly high in the region. For instance, the results of a recently published report by Yale Center for Environmental Law & Policy (YCELP) showed that Jordan ranked third in developing MENA countries, after Tunisia and Morocco, for its environmental performance (YCELP, 2016). The report by the World Bank (2009) also stated that the environmental performance of the country is competitive compared to other developing MENA countries. The country pays attention to environmental development, and thus, the potential of introducing advanced, integrated e-waste management options is predictably possible.

Five studies addressed e-waste issues in Jordan. The first, by Fraige et al. (2012), measured the level of awareness toward e-waste and estimated the domestic e-waste in the country. The second, by Tarawneh and Saidan (2012), aimed to establish an inventory assessment for Jordan's e-waste. The third, by Tarawneh and Saidan (2013), attempted to examine the public's responses and level of awareness of e-waste. The fourth, by Alsheyab (2014), determined the potential recovery of metals and PMs from high-grade e-waste by conducting a mass flow of laptop computers. The fifth, by Ikhlayel (2016), examines the advantages and disadvantages of five methods of estimating e-waste generation. The study discusses the applicability of the methods to developing countries, introduces a method to estimate e-waste generation for developing countries based on the "Consumption and Use" method, and estimates Jordan's e-waste as a case study.

A report by the UNDP (2011) aimed to assess Jordan's e-waste management system by focusing on personal computers and the current situation regarding the legal background, stakeholders involved, material flows, and potential social, environmental, and economic impacts. The report summarized the general overview of and the material flow from the import of e-products as first- and second-hand to the disposal. In summary, and according to the report by the UNDP (2011), three processes exist in the e-waste management system: informal collection, informal recycling, and landfilling. Hazardous materials are sent to a landfill site established for this purpose, informal recycling in which the recycled products are exported to Asian countries. A field trip by the author in 2014 (to Amman city) and in 2015 (to Amman and Irbid cities) involved discussions and interviews with waste management experts, stakeholders, and academics, as well as government officials. The observations from these two field trips and the literature available about waste management issues in Jordan showed that formal recycling facilities do not exist, but pilot projects are available, for example, mobile phone collection and recycling. There is only one sanitary landfill (a well-engineered one established for municipal waste treatment) that receives around 35% of the country's waste. With regards to e-waste handling, several interviewees indicated that storing e-waste is commonly practiced in Amman and its surrounding areas. The findings from the two field trips also indicated no confirmed figures exist on the amount of the e-waste stored or landfilled, nor on the ratio of informal recycling. For the purpose of this study, a 10% recycling ratio for the developed scenarios (for formal recycling) was used, based on several discussions with waste management experts and academics. The amounts going to sanitary landfill sites was not important for this study as the e-waste composition (materials and metals) is entirely landfilled in the first scenario, and only waste residues are landfilled in other scenarios.

1.3. Objective and approach

To mitigate the improper treatment and disposal of e-waste and facilitate the development of e-waste management systems, this paper set the following objective: to evaluate the environmental impacts and benefits of different e-waste management scenarios comprise state-of-the-art technologies.

This study presents a systematic and in-depth approach to modeling the EoL phase in the LCA of small and large electronic devices. The core concept is the need to assess the emissions to the medium (air, water, and soil) from those discarded devices and to evaluate their environmental impacts, both individually

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