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Sustainability evaluation of secondary lead production from spent lead acid batteries recycling

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ABSTRACT

In China, rapid development of electric vehicles resulted in large consumption of lead and lead products such as lead acid batteries (LABs). Recycling LABs is one option to mitigate natural resource depletion and corresponding environmental issues. However, few studies have been conducted to measure the operation of LABs recycling industry. Consequently, it is necessary to initiate such a study so that key barriers on promoting this industry can be identified. Under such a circumstance, this study proposes an emergy-based evaluation framework to evaluate one LABs recycling firm in Yunnan so that the emissions' impact on human health and ecosystem from this firm can be quantified. A set of emergy-based indicators are established to evaluate the sustainability of this recycling firm. The results show that the investigated system had a higher emergy efficiency compared with that primary ore exploitation system. However, the extremely low values of emergy indicators indicate that this recycling system could not achieve sustainable development goals due to its heavy dependence on nonrenewable resources. Based upon such results and local realities, policy suggestions are raised in order to improve the overall sustainability of such a recycling system.

1. Introduction

China' s rapid development was based upon high resource consumption, leading to nonrenewable resource depletion, ecosystem destruction, and serious environmental pollution (Liu and Diamond, 2008). China's GDP has been overstated as it ignores the cost of environmental pollution and ecosystem destruction (Liu and Diamond, 2008). Besides traditional environmental issues, the Paris Climate Change Agreement further required the whole society to pay more attention on climate change issues so that a transition toward a low-carbon society can be achieved (Ali et al., 2017). As the world's largest CO_2 emitter, China has made significant efforts to optimize its energy structure by encouraging renewable energy. Particularly, circular economy and low carbon development have been chosen as the national strategies on addressing these concerns (Liu, 2015; Liang et al., 2014).

One of the most obvious benefits of circular economy is to reduce the extraction of virgin materials from the earth and extend the lifecycle of virgin resources through reduction, reuse and recycling (Geng et al., 2013, 2016), which can alleviate pressure on local ecosystems and natural capitals. To promote circular economy, China issued the Circular Economy Promotion Law in 2008, aiming at improving resource efficiency and achieving sustainable development, Such an action can help economic growth to be decoupled from resource consumption and calls for maximizing the use of recycled materials (Pauliuk et al., 2012). Recently, electric vehicles, which can be considered as one of the most promising clean vehicle options, have received national support in China (Hao et al., 2017). In 2015, China produced over 0.25 million electric vehicles, more than quadrupled over the 2014 level (CAAM, 2016a,b). Such vehicles consumed high amounts of lead and lead products, especially the lead acid batteries (LABs) (Sun et al., 2016). As the world's largest exporter and consumer of LABs, China generated 2.46 million tons of secondary lead in the form of spent LABs in 2014 (Sun et al., 2017). The LABs in-use stocks have rapidly increased from 45 GW h in 2000 to 429 GW h in 2014, with an annual average growth rate of 17.4% (Liu et al., 2016). Under such a circumstance, it is crucial for China to recycle electric vehicles' parts, especially those lead-contained batteries (Hao et al., 2017). Another challenge is that China's overall secondary lead production accounted for 29.3% of the overall lead it produced in 2012, much lower than that in U.S.A (more than

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80%), Europe (90%) and the global average (60–66%) (Zhang et al., 2016). Besides, secondary lead production is one environmentally challenging industry due to its corresponding environmental issues, such as open-air smelting, wastewater discharge and final disposal of lead. Particularly, long-term exposure to lead can cause decreased performance of nervous systems and nephropathy for the adults. It can also affect brain development among children (Gottesfeld and Cherry, 2011). Due in large part to inefficient management of lead production, there have been severe environmental disasters in China. Ten lead poisoning accidents have happened in China since 2009, leading to more than 4000 children affected (Sun et al., 2017). Because of heavy pollution from recycling lead, more than 70% of Chinese lead recycling plants were closed in 2012 (Tian et al., 2014). Therefore, it is critical to improve the sustainable operation of China's secondary lead industry so that they can reduce their overall emissions and increase their resource efficiency.

Factors influencing sustainable development of this recycling industry were investigated from various aspects, including material flows, economic performance, energy consumption, environmental pressures, etc. For instance, Genaidy et al. (2009) adopted an evidence-based method to propose strategies to increase lead recovery and recycling efficiency after examining lead recycling systems from the aspects of pollution prevention, waste minimization, technical and economic feasibility. Liu et al. (2016) employed a bottom-up method to quantify the lead in-use stock in LABs and developed a model to forecast the lead in-use stocks until 2030. Tian et al. (2017) compared the environmental impacts and economic differences of five typical LABs recycling processes in China by using the Chinese life cycle database. However, few studies have evaluated LABs recycling production systems with the aim of evaluating the ecosystem's contribution and the overall eco-efficiency of such a recycling system. Actually, ecological products and services should be accounted into social and economic production so that their real contribution can be quantitatively evaluated (Pan et al., 2016a). Without a scientific evaluation of such contributions, it will be difficult for decision makers to seriously consider the protection of natural ecosystem and consequently allocate necessary resources to support this recycling industry's sustainable development.

Academically, Geng et al. proposed to measure China's circular economy by employing emergy synthesis (Geng et al., 2013, 2016). Emergy accounting (EMA) measures the contributions of ecosystem to production systems from any scale in comparable units and accounts the real wealth generated by nature and by humans (Odum, 2007). Such a holistic accounting of the whole supply chain can assign environmental impacts more fairly which in turn can discourage inefficient and unnecessary resource depletion (Geng et al., 2013). Many researchers adopted EMA to study the recycling industry in the past. For instance, Brown and Buranakarn (2003) proposed several emergy based indices to evaluate the recycling performance of municipal and construction wastes. Song et al. (2012) improved traditional emergy indicators to evaluate the sustainability of an e-waste treatment enterprise by considering factors such as environmental impact and metal recycling. However, the results of their study do not reflect the waste emissions' impacts on human health and ecosystem. Similarly, biomass recycling systems have been studied by Wang et al. (2017) in which traditional emergy yield ratio (EYR) and emergy sustainable index (ESI) were modified to evaluate the impacts of applying recycled biomass through a case study of one wheat-maize double-cropping system fertilized by different sources. Other examples of EMA to study recycling systems include those involving building materials (Amponsah et al., 2012), construction and demolition wastes (Yuan et al., 2011), waste exchanges within one industrial system (Zhang et al., 2010), recycling of end-of-life vehicles (Pan and Li, 2016), reverse logistic networks for steel (Giannetti et al., 2013), photovoltaic panels (Corcelli et al., 2016), etc. These studies demonstrate the effectiveness of EMA for different recycling industries to that effective policies can be raised. However, to the best of our knowledge, few EMA based studies on evaluating the comprehensive performance of spent LABs recycling industry have been published

Under such a circumstance, this study aims to propose a systemic evaluation framework by applying EMA so that the holistic impact of spent LABs recycling industry can be evaluated, including collection, sorting and processing. A case study approach is employed so that more practical perspectives can be observed and more feasible policies can be prepared to improve the sustainable operation of this recycling industry. The rest of this paper is organized as follows. Section 2 introduces the investigated system, research methods and data. Section 3 presents results and discusses policy implications. Finally, Section 4 draws research conclusions and provides policy suggestions.

2. Methods and data

2.1. A short introduction of the LABs recycling system

This paper employs a case study approach. The case enterprise is one LABs recycling enterprise located in Gejiu city of Yunnan province, China. This enterprise covers an area of 41,700 m^2. The sources of spent LABs include electric vehicles, electric bikes and uninterruptible power supply (UPS) systems. These LABs consist of 21 wt.% electrolyte, 24.4 wt.% lead grid, 48.5 wt.% paste lead, with the remaining portion consisting of plastics and organic materials. Lead grid and battery paste are two major secondary lead resources contained in the spent LABs. This enterprise is using pyro-metallurgy technologies to recycle spent LABs. The three major recycling processes include pretreatment of the spent LABs, lead smelting & refining, and sodium sulfate production. The pretreatment process includes breaking, crushing and physical separation, in which the spent LABs are separated into lead grid, battery paste, polypropylene, sulfuric acid and plastic materials. Sulfuric acid is subsequently sold to an acid production plant for further purification. Similarly, polypropylene and plastic materials are also sold for further processing. The battery paste is desulphurized by adding desulfurizing reagent. The desulphurized battery paste is smelted at a temperature above 1000 °C, while lead grid is directly smelted to produce lead-antimony alloy. After smelting, the lead bullion is refined to produce lead ingot. The sodium sulfate solution from the desulphurized process is made into sodium sulfate through filter pressing and crystallizing. The products of this enterprise are finally sold in the market.

The basic reactions of this production system can be expressed as follow:

$$PbSO_4 + Na_2CO_3 \rightarrow PbO + Na_2SO_4 + CO_2 \tag{1}$$

$$2PbO + C \rightarrow 2Pb + CO_2 \tag{2}$$

$$PbSO_4 + 2C \rightarrow PbS + 2CO_2 \tag{3}$$

$$PbS + Fe \rightarrow Pb + FeS \tag{4}$$

The flowchart of this investigated enterprise is shown in Fig. 1.

2.2. Emergy based environmental accounting

Emergy accounting (EMA) is grounded in thermodynamics and general system theory. Emergy can be defined as "the total amount of available energy (usually solar) that is directly and indirectly required to make a given product or to support a given flow" (Odum, 1996). As an environmental evaluation tool, emergy assesses the contribution of natural resources to economic activities or measures cost of production on the spatial and time scales of the biosphere (Geng et al., 2013). Besides, distinctions between qualities of resources, energies and services can be enabled by employing such a method. For example, one MJ from oil or wood contributes the same amount to indicators in energy analysis, however oil or wood are made by different production patterns and times within natural cycles requiring different environmental work (Geng et al., 2013). The advantages of EMA can be summarized