Journal of Environmental Management xxx (2016) 1–5

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Assessing the sustainability of lead utilization in China

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ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form
22 May 2016
Accepted 25 May 2016
Available online xxx

Keywords:
Lead
Sustainability
Utilization
Material flow
Management
China

ABSTRACT

Lead is not only one of heavy metals imposing environment and health risk, but also critical resource to maintain sustainable development of many industries. Recently, due to the shortage of fossil fuels, clean energy vehicles, including electric bicycle, have emerged and are widely adopted soon in the world. China became the world's largest producer of primary lead and a very significant consumer in the past decade, which has strained the supplies of China's lead deposits from lithosphere and boost the anthropogenic consumption of metallic lead and lead products. Here we summarize that China's lead demand will continually increase due to the rapid growth of electric vehicle, resulting in a short carrying duration of lead even with full lead recycling. With these applications increasing at an annual rate of 2%, the carrying duration of lead resource until 2030 will oblige that recycling rate should be not less than 90%. To sustain lead utilization in China, one approach would be to improve the utilization technology, collection system and recycling technology towards closed-loop supply chain. Other future endeavors should include optimizing lead industrial structure and development of new energy.

1. Introduction

With the rapid economic development, China has become the largest manufacturing producer in the world, and a major foundry of electric components (Zeng and Li, 2013). Meanwhile for mineral resources in particular, which are nonrenewable, the severe pressure of resource shortage has gradually become an issue of national concern (Zhang et al., 2015), thus new energy vehicle (EV) has emerged and is widely used in the world, which leads to the share of traction batteries continuously increasing (Tian et al., 2015). Lead-acid batteries are a major component in the battery technology (Deveau et al., 2015; Higgins et al., 2007; Neto et al., 2016; Tian et al., 2014). To respond to the large domestic and international demand for electric bicycle, it is predicted that the output of the electric bicycle will reach 32 million in China in 2015. China has become the world's largest producer of primary lead and a very significant consumer in the past decade (Liu et al., 2016; Roberts, 2003). This boom, however, has strained the supplies of China's lead deposits and boost the consumption of metallic lead and lead products (Ma, 2013).

Lead is not only one of heavy metals imposing environment and healthy risk(Canal Marques et al., 2013), but also critical resource to maintain sustainable development of many industries. The emergence of sustainability as a goal in the management of environmental resources is a result of the growing global environmental concern (Vatalis, 2010). According to the U.S. Geological Survey (USGS), the total reserve of lead all over the world shows an increasing trend from 68 million metric tons (Mt) in 2002 to 87 million metric tons in 2014, and China ranked the second with 14 Mt (Ma, 2013; U.S. Departmentof the Interior). However, China's reserve structure is improper and the lead raw material remains in short supply inland (Ma, 2013). The extraction and consumption of metals has increased along with economic development (Henckens et al., 2014). Globally, the battery industry is the largest consumer of lead in the world (Battery Council International, 2015) and some researchers found that nearly 80% of lead is currently employed in batteries and the global scrap recycling rate is very high (Genaidy et al., 2008; Lopez et al., 2015; Roberts, 2003; Zhang et al., 2014). Lead oxide is another main application form of consumption, accounting for approximately 13% of refined lead consumption, and lead alloys and lead materials only take of 6% (Ma, 2013).

To response to the tense situation, lead recycling is obliged to be carried out with high efficiency, driven by superior characteristics of secondary lead— low energy consumption and low cost (at an annual rate of 2% et al., 2013; Cherry and Gottesfeld, 2009). Moreover, recycling is beneficial to the environment as far as

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http://dx.doi.org/10.1016/j.jenvman.2016.05.063
0301-4797/

environmental release rate concerned. Resource management is a key factor for sustainable development (Agudelo-Vera et al., 2011), so official policy in China should be proposed to stimulate the sustainable utilization of lead. However, most problems related to natural resource management and conservation are plagued with high levels of uncertainties, which can lead to a hard decision (Fackler and Pacifici, 2014; Gret-Regamey et al., 2013) and successful policy should be based on the market and the industry (Hagelstein, 2009). Some scholars has used material flow analysis (MFA) of lead and presented some forecast (Lan Ma, 2014; Mao et al., 2007, 2008a). However, the sustainability of China's lead reserve subjected to industry development remains unknown. Hence, in this work, the current material flow of lead and the condition of demand for lead in different industries are greatly necessary to be investigated. And more, for the sake of sound sustainability of lead in the future, we will demonstrate the relationship between supply and demand in various scenarios of lead industry development.

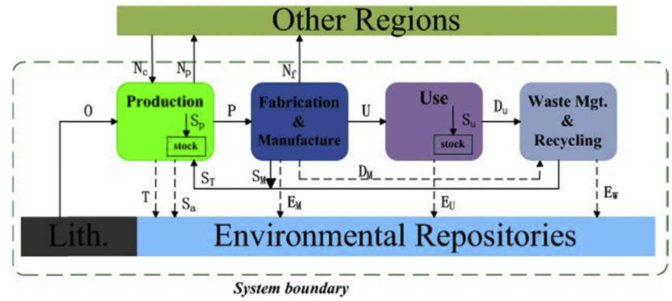

Fig. 1. Framework for analysis of lead flows within China. where: O = domestic consumption of ore; N_C = net exports of lead ore; T = tailing; P = domestic consumption of refined lead; N_P = net exports of refined lead; S_a = slag; U = consumption of lead product; N_f = net exports of lead product and semi-finished product; E_M = lead losses during fabrication and manufacture; D_U = amount of lead wastes; S_M = lead to be refined; E_U = lead losses during use stage; S_T = amount of recycled leas; D_M = lead recycled during fabrication and manufacture; E_W = lead losses during recycling; S_P = stock of refined lead; S_U = stock of lead production.

2. Data and methods

2.1. Available data related to lead and lead application

USGS reported in 2014 that lead reserve in China is around 14 Mt, accounting for 16% of the world supply (U.S. Departmentofthe Interior). The identified lead reserves are located mainly in Yunnan, Inner Mongolia, Guangdong, Qinghai, Gansu, Hunan, Sichuan, Xinjiang, Jiangxi and Fujian, revealing an uneven distribution (Ma, 2013). Most of the creditable data are collected from national statistics, national plan or state report. Other data are extracted from some authoritative published papers.

2.2. Material flow analysis of lead

The metabolism of a production process can be demonstrated by identifying all the material or substances that flow into or out of the production system (Bai et al., 2015). Quantifying the stocks and flows of a metal throughout its life cycle can be useful for understanding patterns of resource use and losses of metal into the environment; it can also guide resource and waste management policies in a given region (Carl Johan Rydl, 2003; Spatari et al., 2005; Wen et al., 2015). The MFA model is made up of four main components or life stages: production, fabrication and manufacturing, use, and waste management (Clift and Druckman, 2016; Mao et al., 2008b; Spatari et al., 2005). In this paper, we will follow the model. Fig. 1 shows the physical framework of processes and reservoirs for analyzing lead flows and stocks.

2.3. Scenario analysis for annual and cumulative demand of lead

According to Chinese statistics, annual increment of lead consumption is shown in Table 1, from which 4.95 Mt is forecasted by experts in an official seminar. Obviously, the annual increment approximately trends to be stable at 2% by reason of the industrial restructuring in the past two years. All things considered, we assume that lead demand growth rate is stable at 2% in the next few years. Thus, the consumption status can be forecasted in terms of the consumption for the former year indirectly. In consideration of the possible energy structure adjustment in the future, we also assume the growth rate at 0 and -2% for comparison.

2.4. Scenario analysis under different recycling rate

Here, carrying capacity is defined as the supporting maximum amount by lead reserve. Carrying duration of lead reserve is the supporting time, affected by the increasing rate of lead applications and the recycling rate of lead products (Zeng and Li, 2013, 2015). Clearly, refined lead is supported with ore, and also influences the production, consumption, and export, which is of vital importance. The increasing rate of lead applications and the recycling rate of lead products can be estimated by the following equation:

$$D(t)_{\Psi,\eta} = 485(1+\Psi)^{\tau} - D(t-2)_{\Psi,\eta} \times \eta \quad (1)$$

where $D(t)_{\Psi,\eta}$ is the lead demand quantity of *t* year, τ—time (year) and where is the basic values in 2014,Ψ—demand growth rate,and η—recycling rate.

3. Results and discussion

3.1. Material flow analysis of lead

Based on the existing researches (Higgins et al., 2007; Mao et al., 2007) and statistical data (Hu, 2013), the lead flows is demonstrated in Fig. 2, which are obtained based on the premise of the following assumptions:

(1) There is not obvious progress in lead smelting technology, so tailings and slag generated from unit age of ore in the same condition are identified from 2010 to 2014,
(2) There is not improved technology in the process of production, manufacturing and recycling, so waste residue generated from unit age of refined lead is constant from 2010 to 2014, and
(3) The proportion of lead released to the environment during each procedures remains unchanged from 2010 to 2014. According to on some researchers' calculation (Jing Liang, 2014), the ratio of lead released to the environment during production, fabrication and manufacture, use and waste and recycling are 21.9%, 4.8%, 36.9% and 36.4%, respectively.

On the basis of that hypothesis and the statistic data, frame diagrams of lead material flow in 2000, 2006, 2010, and 2014 are shown below. Through comparing the four situations, present lead utilization situation and deficiencies are applied to better solution to lead pollution and waste management.

According to the obtained results, demand for refined lead and lead products is increasing gradually. To response to the growing demand of lead, lead ore exploitation is also growing meanwhile. Moreover, greater import of lead ore is in process and export of