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Uncovering the evolution of substance flow analysis of nickel in China

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ABSTRACT

Nickel is playing a pivotal role in development of modern infrastructure and technology with major applications such as stainless steel, alloy, rechargeable batteries and electroplating. Rapid industrial development and economic growth of China has accelerated the depletion of natural resource pools since recent three decades. Therefore, this study was performed to examine the evolution of substance flow of nickel. Main findings include the following: 1) China is being confronted the increasing risk of uncontrolled importation; 2) The consumption amount has been constantly extended up to 1010 Gg in 2015, however the obsolescence amount is almost remained at an unchanged range of 45–50 Gg; 3) If more nickel has been stocked in the consumption stage and landfill plants, only 30% is recycled. The obtained results implied that China should not only find more sources of imported minerals, but also there should be an enhancement of the urban mining for nickel resources in the circular economy field.

1. Introduction

The availability and usage of various metals has been much important to the evolution and development of modern society that historians named major human epochs after them, as exemplified by the Bronze, Iron, and Atomic ages (Mudd and Jowitt, 2014). Nickel is a metal that dominantly reflects with the technological advances of the twentieth and twenty-first centuries, emerging as potentially important for manufacturing stainless steel, various kinds of special metal alloy, currency and rechargeable batteries as well as for electroplating (Ciacci et al., 2016; Reck et al., 2008). Nickel is mainly used for making stainless steel and other alloy stronger and better which is able to withstand extreme temperatures and corrosive environments.

China has become the largest consumer and importer of nickel resource in the world. In 2013, China's nickel consumption accounted for over 50% of global utilization (Zeng et al., 2015b). Geologically, China has only 3000 Gg (1 Gg = 1000 tons) reserve (economically mineable resource) and 7643 Gg reserve bases (demonstrated resource). However, China's nickel reserve is only accounting for 3.7% of global reserves with two notable features of high grade and concentrated distribution (USGS, 2015; Zhang et al., 2013; Zhou et al., 2015). Worldwide, rapid depletion of metals is calling for sustainable mining and utilization of resources (Ghaderi et al., 2014).

Many works related to anthropogenic metals and those sustainability have been carried out in the recent decades (Chen and Graedel, 2012; Gauffin et al., 2016; Rauch, 2009). The availability and carrying capacity of resources are the most extensive problems related to survival and continuation of the metals industry which has to contend with (Alonso et al., 2012; Golev and Corder, 2015; Graedel, 2011; Weiser et al., 2015). Furthermore, many metals have been concerned for their stocks and sustainability in the whole world or in China since 2000 (Reuter et al., 2013; Wang et al., 2008; Zeng and Li, 2015).

So far, few attempts to quantify nickel cycle have been carried out (Huang et al., 2014; Reck et al., 2008), but the these findings were outdated and there is no insight about the evolution of substance flow analysis of nickel. Therefore, this study is devoted to estimate the nickel flow from lithosphere to technosphere, and uncover China's evolution of nickel flow in recent two decades.

2. Data and methods

2.1. Data

The life cycle of nickel flow covers natural mining, export & import, manufacturing, consumption, obsolescence as well as waste recycling & disposal (Zeng and Li, 2017). All relevant data covering the life cycle was needed to collect information for this study. The data related to nickel mining, importation, exportation, recycling, and consumption is presented in Table 1 and Fig. 1. However, the importation data of nickel-containing electronic waste (e-waste) was not available.

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Table 1
Consumption of nickel applications in China from 2004 to 2014 (Gg).

Year	Stainless steel	Battery	Electroplating	Non-ferrous alloy	Others	Sum
2004	62	13.5	48.0	15.0	12.0	150.0
2005	87	14.3	44.1	14.4	9.8	169.7
2006	117	12.8	34.7	7.3	10.9	182.4
2007	174	18.1	41.5	10.4	15.5	259.1
2008	228	16	49	26	10	330
2009	313	16.3	40.7	28.5	8.1	406.7
2010	406	16.0	53.4	26.7	32.0	534
2011	526	27.3	68.3	47.8	13.7	650
2012	677	24.8	74.3	41.3	8.3	683
2013	701	19.5	57.75	33	13.75	825
2014	840	21	62.8	1.25	4.85	930
2015	860	25	63	20	14	982
2016	920	27	64	56	43	1090

Note: The data from 2004 to 2014 is estimated by the consumption structure and total consumption (Luo, 2013); and the data for 2015 and 2016 from the ref. (Xu, 2017).

Two decades ago, a massive amount of global e-waste was reportedly dumped in China. And also, since 2002, Basel Convention and China e-waste regulation was enforced and illegal *trans*-boundary of e-waste has been continually declined (Wang et al., 2013; Zeng et al., 2013). In addition, the average concentration of nickel in all types of whole e-waste was artificially low which may be less than 0.01% (Robotin et al., 2013). Meanwhile, waste importation was strictly regulated when the State Council released action plan to phase out waste imports on July 27, 2017 (State-Council, 2017). Hence, the imported nickel-containing waste was not considered to determine the substance flow of nickel in this study. Atmospheric nickel emissions can be neglected because nickel smelting only contributed to around 0.1Gg at the duration of 1980–2009 (Tian et al., 2012). The dissipation released to the environment during nickel flow is trivially compared to use and obsolescence; the related data is negligible here.

2.2. Method

Substance flow analysis has been employed widespreadly in uncovering metal cycle and urban metabolism (Muller et al., 2014; Rechberger et al., 2014). Basically, nickel cycle consists of four main stages; importation/exportation, production/application, obsolescence, and recycling. Classic framework of substance flow (Brunner and Rechberger, 2016; Guo and Zhang, 2016; Sun et al., 2016) can formulate China's nickel utilization which is demonstrated in Fig. 2.

Mass balance law was utilized here to calculate the nickel flow with the following Eq. (1).

$$stock = \sum input - \sum output \quad (1)$$

Where *stock* is the net stock of nickel in one stage, *input* is various roads of nickel flow into the stage, and *output* is various roads of nickel flow out the stage. For instance, the stock of nickel production can be determined by the formula of $S_u = U\text{-}D_u\text{-}E_u$.

Considering China's actual situation, many parameters shown in Fig. 2 can be simplified. Except exportation of battery, alloy, catalyst, and magnetic material, other nickel is applied domestically. Inevitably, nickel applications are obsolesced or discarded so that more and more nickel is destined to stock in waste. At obsolescence, waste can be recycled or recovered for regeneration. But often due to improper collection system and recycling technology, only a part of nickel could be recycled, which means that the enormous nickel is stored in waste and some are generally destined for unwanted landfills (Nakajima et al., 2016). During nickel recycling, some nickel-containing waste is illegally imported into China, and in most cases, they are commonly regarded as hazardous waste like toxic e-waste (e.g. printed circuit board, and cathode-ray tube) (Kumar and Holuszko, 2016; Li et al., 2013; Ylä-Mella and Pongrácz, 2016). Nickel dissipation mainly occurs in the processes of mining, manufacturing, and recycling, which is ignored owing to small amount (Lu et al., 2015; Wang et al., 2017). Nickel scrap yield from manufacturing was also not considered in this study without direct information.

3. Results and discussion

3.1. Source of nickel supply

Initially, China's nickel is supplied from three sources; import of raw materials, domestic mineral mining, and waste recycling. Importation is the predominant source of nickel demand for China, which was enhanced by the decrease of self-sufficient rate from 60% in 2005–10% in 2013 (Fig. 1). Meanwhile, imported nickel metal majorly weighs over 200 Gg (1Gg = 1000Mg = 1000 tons), although a decline occurred from 2000 to 2014 because some countries have reduced their exportation (Fig. 1). China's imported nickel mineral in 2015 was from roughly 40 countries or regions, covering Asia, America, Europe, and Oceania which is also presented in Fig. 1. According to this figure, Philippines has been acted as a leading country for nickel importation, followed by Indonesia, Russia, and Australia. However, Statistics of China mineral indicated that the importing landscape in terms of importers and importation has changed dramatically from 2014 to 2015 (SC Table S1). It reveals that China confronts with the increasing risk of uncontrolled importation (Fig. 3).

In light of production and consumption of nickel in China from 2005 to 2014 (Fig. 1), individual cycles tracing nickel flows through production, application, obsolescence, and recycling were established for 2000, 2009, 2011, and 2015 (Fig. 4). Total demand of nickel in 2015 has significantly increased from 400% of the amount that in 2000, which can meet the needs of 66–78% and 22–34% for domestic consumption and export, respectively. Regarding nickel supply, import was dominant at the rate of 82–90% until 2011. Then owing to the limitation on import to China, China had to extract the domestic stored nickel between 2012 and 2013 (Zeng et al., 2015b). Therefore, the landscape of nickel supply has been distinctly changed; the rate of import decreased from 90% to 8%, and meanwhile domestic mining increased from 3% to 83% (Fig. 1).

3.2. Production and applications

Consumption of nickel applications (Table 1) and nickel production (Fig. 1) provide the basic insight of production and applications. Within just 5 years range of 2005–2010, China passed such traditionally strong stainless steel producers and users as Japan, USA, Germany, and South Korea to become the dominant player of the stainless steel industry. However, China did not produce any significant stainless steel end-of-life (EoL) flows in 2000 or 2005 because its products-in-use are still too new to require replacements. Major discard flows are expected to begin between 2015 and 2020 (Reck et al., 2010).

As a result, nickel applications were increased from 189 Gg in 2000–1160 Gg in 2015. These applications were primarily supplied by domestic production and imported production. Rapid growth of domestic production has caused that the share of imported production is declining which was less than 18% in 2015 (Fig. 1(B)). Relatively more demand from domestic production is needed to maintain the nickel consumption industry. However, the actual utilization of imported nickel in 2015 (Fig. 4) is much above the current importation (Fig. 1(B)) because the imported nickel mining in 2015 covers the store of previous imported mineral.

3.3. Consumption and obsolescence

Consumption of nickel products to fulfill the optimal function is the basic purpose of anthropogenic activity. Thus, to maximize the flow to