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Substance flow analysis for nickel in mainland China in 2009

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ABSTRACT

A comprehensive understanding of the flows and stocks of non-renewable resources plays an important role in the development of sustainable resource use policies. Substance flow analysis (SFA) is an established method to comprehensively analyze resource flows in the anthroposphere, and this paper conducts a quantitative SFA for nickel in mainland China for the year 2009. The analysis shows that total available primary nickel, total available nickel used in fabrication processes and in-use stock of nickel end-products during the year 2009 were 509.28 Gg, 647.25 Gg and 341.83 Gg respectively, and the net import reliance was about 73%. Some sustainability indicators can be derived from the SFA results, and these indicate that the sustainability of the Chinese nickel industry chain could be significantly improved. However, to conduct a comprehensive assessment of resource sustainability it would be necessary to derive systematic SFA indicators. The overall environmental burden exported from the Chinese nickel industry is greater than the imported burden, with the imported environmental burden resulting mainly from the smelting and refining of imported nickel ores. The results indicate that cradle-to-cradle management is important for Chinese nickel industry, including shrinking the milling and refining capacity, improvements to processing technology, and enlarging the capacity for domestic and imported waste management.

1. Introduction

Nickel (symbol Ni, atomic weight 58.71, atomic number 28) is a lustrous, silvery-white metal which is widely used in more than 300,000 different products (International Nickel Study Group, abbreviated as ‘INSG’, http://www.insg.org/whatnickel.aspx). About 61% of new nickel produced worldwide is used to manufacture stainless steels, 9% is used in other nickel alloys, 13% is used in plating, and 17% in other uses, including batteries, catalysts, and chemicals (Bradley, 2011). Reck et al. (2008) divided end-use nickel products into the five categories of building and infrastructure, transportation, industrial machinery, household appliances and electronics, and metal goods. In many of these applications, there is no substitute for nickel which can be used without reducing performance or increasing costs.

Although nickel is Earth’s fifth most common element, commercially exploitable reserves are limited. The use of nickel has grown exponentially over the past century, and approximately half of all nickel in circulation was put into use between 1980 and 2000 (Reck et al., 2008). In 2004, the estimated Ni content of the global nickel laterite resource available using current extraction technologies was 161,000 Gg (Dalvi et al., 2004). In 2008, global economic and sub-economic nickel resources were estimated at 220,000 Gg Ni (USGS, 2009). If the growth in world nickel consumption continues at current rates, this would be consumed within about 50 years (see Eq. S(1) in the Supplementary data).

The recent increase in primary nickel consumption has been driven by rapid development of the stainless steel industry. China has become the world’s largest producer and consumer of stainless steels (Xu, 2008), accounting for less than 36% of world nickel consumption in 2009, a total which increased to more than 43% in 2011 (Table S1, Supplementary data). Chinese nickel reserves are only 18 times greater than present annual primary nickel consumption, and available nickel from waste and scrap is limited. China therefore has an increasingly important role to play in supporting sustainable use of global nickel resources, and the identification of potential savings in the processes of nickel production, consumption and recycling is an urgent task.

Substance flow analysis (SFA) is an analytical method used to systematically assess the flow and stock of a substance through a given system (e.g. productive system, economic or social system),

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which should be clearly defined in space and time (Bringezu et al., 1997; Brunner and Rechberger, 2004; Hendriks et al., 2000). SFA monitors flows of individual substances that raise particular concerns regarding the environmental and/or health risks associated with their production and consumption, and uses the principle of mass balancing to analyze the relationships between substance flows, human activities and environmental changes (OECD, 2008). Static SFA models can be used to identify the causes of pollution problems and to assess the effectiveness of management measures (Udo de Haes et al., 1997), while dynamic SFA models include stocks and materials-in-use (Bergbäck and Lohm, 1997). Stocks and materials-in-use are often the major cause of disconnection between system inflow and outflow in a given year, meaning that dynamic SFA models lead to more accurate prediction of future resource use and waste streams (Elshkaki et al., 2005).

Nickel improves austenitic steel's structural stability, oxidation resistance, high-temperature strength, and room-temperature ductility. However, a sustainable stainless steel industry depends not only on a sustainable supply of nickel ores, but also on whether nickel products are produced, consumed and recycled throughout their entire lifecycle in a sustainable way. For example, material flow analysis indicates that if austenitic stainless steel were to be produced solely from scrap, energy use would be 67% less than ore-based production and CO_2 emissions would be cut by 70% (Johnson et al., 2008). Thus, nickel SFA can be used to help to assess the sustainability of nickel resource use, by understanding use and loss characteristics as well as the balance between supply and demand. Nickel SFA can also indicate how demand can be systematically reduced through improvements in nickel flow and recycling.

Some anthropogenic nickel flow processes have already been analyzed. The anthropogenic nickel cycle for the year 2000, especially the import/export and recycling of discarded nickel, has been analyzed at multiple levels, including 52 countries, territories, or country groups, eight regions, and the entire planet (Reck et al., 2008), while Matthew (2010) analyzed energy requirements and greenhouse gas emissions from the entire global nickel industry. Other studies include regional material flow analysis of products containing nickel, for example, lithium batteries (Chang et al., 2009) and spent hydrogenation catalyst (Yang et al., 2011). However, this study is the first to attempt a thorough integrated nickel flow analysis at the country level, and also discusses the role which SFA results can play in the derivation of sustainability indicators and analysis of environmental burden shifting.

2. Methodology and data preparation

2.1. Substance flow analysis

Following standard SFA procedures, our study included the following steps:

(1) Research objective and system definition

This study analyzes the anthropogenic nickel cycle in mainland China (excluding Hong Kong, Macao and Taiwan) in the year 2009.

(2) Data collection and SFA framework formulation

The results incorporate information from INSG, public data from government and/or industrial organizations, literature, market research, expert judgment, best estimation, and direct interviews with miners, manufacturers, importers, exporters, and so on. A full list of data sources used in this study can be found in the Supplementary data. Based on these data sources, we established a substance flow system during the four stages of production, fabrication and manufacturing, consumption, and waste management, as shown in Fig. 1.

(3) Mass balancing

Based on the principle that mass-in is always equal to mass-out (Fig. 1), simple mass balance formulas can be created, such as Eq. (1). Nickel mass flow data was then calculated and checked, and a nickel flow chart was created.

$$I = O/(1 - \mathrm{LR}) \quad (1)$$

Where I is nickel input into a process; O is nickel output from the process; LR is nickel loss rate during the process; and $1 - \mathrm{LR}$ is the recovery rate.

(4) Interpretation of results

Based on the nickel flow chart, both the sustainability of nickel resource use and environmental burden shifting were assessed by analyzing the environmental performance of nickel flow, import and export of Ni mass, resource use efficiency and the balance of supply and demand.

2.2. Data sensitivity analysis

At present, there is no relevant nickel SFA database available in China. Insufficient information was available to specify uncertainty for some stock and flow data. Based on the collective judgment of the authors regarding the reliability and quality of the data, high confidence data include INSG data, official data, estimated or validated data mainly based on official data and INSG data, and data of a similar quality from other sources. Lower confidence data include the authors' estimated values mainly based on unofficial data sources, such as published literature whose data may be from specific experimental conditions, industrial reports where the data may be affected by economic interest or reporters' attitude, and so on. However, all data in the Results have been validated by mass balancing, and most are similar to INSG or official estimates, which tend to confirm our estimates for some missing data, and is in accordance with the history and present situation of the Chinese nickel industry. Detailed calculations can be found in the Supplementary data.

2.3. Background and assumptions for nickel SFA

(1) Chinese demand for primary nickel continues to escalate (Kuck et al., 2010). Net imports of products of nickel ores and concentrates, primary nickel, and stainless steel waste and scrap all increased between 1999 and 2009 (Fig. 2). As primary consumption is increasing more quickly than primary supply, supply gaps for nickel ores and primary nickel increased between 1998 and 2009 (Fig. 3).
(2) The London Metal Exchange (LME) nickel price has decreased sharply since 2007 (INSG, 2010), which may lead to further increase in demand for nickel.
(3) Many of the stimulus programs implemented in response to the 2008 global economic slowdown funded electricity generation, transportation, and other major infrastructure projects that require large tonnages of nickel-bearing stainless steel and super-alloys (Kuck et al., 2010), especially 300 series (austenitic) stainless steel (Chen, 2012). Nickel demand will continue to increase rapidly in line with stainless steel production, particularly in mainland China. In 2009, Chinese nickel demand exceeded domestic nickel supply by 188.7 Gg (Fig. 3).

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