Resources, Conservation & Recycling 139 (2018) 188–193

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Full length article

Examining the sustainability of China’s nickel supply: 1950–2050

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ARTICLE INFO

Keywords:
Nickel
Sustainability
Recycling
Resource utilization
China

ABSTRACT

Rapid economic growth and accelerating urbanization in the past three decades have accelerated the exhaustion of China’s mineral resources. China is the world’s largest consumer and importer of nickel resources; therefore, a growing domestic demand will increase China’s import dependence and in turn make it potentially vulnerable to supply shortages. One hundred years from 1950 to 2050 were examined for China’s nickel utilization. Identified domestic nickel resources can only sustain China’s industries until 2017, but nickel will reach peak utilization around the year of 2020–2022. Given the 5% annual increase in applications and the growing importation of minerals in China, the carrying duration of nickel resources until 2020 will require a nickel-recycling rate of more than 90%. To sustain China’s nickel utilization, future strategies should foster three solutions: maintaining a high level of imports, adjusting the landscape of nickel applications, and shifting from virgin mining of geological minerals to urban mining of anthropogenic resources.

1. Introduction

The availability and utilization of various metals are so indispensable for human society that historians have named major human epochs after them, such as the Bronze Age and Iron Age (Mudd and Jowitt, 2014). Since the 2000s, anthropogenic metals have been studied for their reserves, flows, and stocks (Ellis and Trachtenberg, 2014; Guo and Zhang, 2016; Liu et al., 2016; Rauch, 2009). Like “peak oil”, “peak minerals” represents the upper limit of the annual production of specific minerals. Although humans may not physically ‘run out’ of metal minerals, the concept of “peak minerals” does appear to be significant, as the timing and scale of the peak have underlying societal impacts due to the critical role metals play in modern society (Daw, 2017).

Among various metals, nickel plays a special role in the technological advances of the 20th and 21st centuries and is a mainstay of modern industry and civilization because of its applications in stainless steel, a variety of special metal alloys, coins, electroplating, and rechargeable batteries (Reck et al., 2008). A changing economic geography of nickel mining and production over time is moving from Russia and Canada to New Caledonia, Australia, Brazil and most recently to Indonesia and the Philippines (AHP et al., 2017; Mudd, 2010). Thus, the sustainable mining and utilization of nickel have increasingly become a global concern (Gulley et al., 2018; Izatt, 2016). China has become the largest consumer and importer of nickel. In 2013, China’s nickel utilization accounted for more than 50% of global utilization (Zeng et al., 2015). Nevertheless, China had only 3.0 Mt (1 Mt = 1 × 10^3 kt = 1 × 10^6 ton) of nickel reserves in 2012, dropping to 2.9 Mt in 2017 (see Table S1 in Appendix A), and 7.643 Mt of reserve bases, accounting for only 3.7% of global reserves (Zhang et al., 2013; Zhou et al., 2015).

As the proportion of the nickel ore stock remaining in the lithosphere diminishes relative to the stock-in-use and stock dissipated (Lederer et al., 2016), the increasing scarcity of nickel ore is expected to stimulate recycling well above the current level of around 30% (Zeng et al., 2018). Indeed, the expected reserve depletion and demand increase for nickel have motivated China to aggressively recycle end-of-life (EoL) nickel products (Wen et al., 2015), also called solid waste or anthropogenic resource (Wang et al., 2017). However, the effect of nickel recycling (or urban mining) on future supply and demand, and on the timing and scale of “peak nickel” remains unknown. Consequently, we intend to investigate the evolution of nickel flow in China, measure the sustainability of geological nickel resources subject to the rapid development of the stainless steel industry, and demonstrate quantitatively how nickel recycling affects peak nickel utilization in China.

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https://doi.org/10.1016/j.resconrec.2018.08.011
Received 14 March 2018; Received in revised form 15 August 2018; Accepted 16 August 2018

2. Materials and methods

2.1. Materials

The distribution of geological nickel in China is highly dispersed (Fig. S1) and is concentrated in a handful of provinces, including Gansu (62%), Xinjiang (11.6%), Yunnan (8.9%), Jilin (4.4%), Hubei (3.4%), and Sichuan (3.3%). Nickel supply for China is commonly fulfilled with virgin mining of geological ores, recycling, and imports of ores and intermediate products. Total nickel demand, however, consists predominantly of exports of nickel-containing products and domestic utilization from stainless steel, electroplating, alloy, and battery. We collected and analyzed all available data related to China's nickel supply and demand at the duration of 1949–2016 (Fig. S2 and Tables S1–S3).

2.2. Methods

2.2.1. Scenario analysis for nickel demand

Resource demand scenarios are critical to measure the resource sustainability (Elshkaki et al., 2018). Regarding the recycling of EoL products, one of the simplest approaches to uncover future nickel demand is the Time Step Method, which uses linear regression analysis. Specifically, using the data provided in Table S3, linear regression analysis can be used to determine the increasing rate and future nickel demand. Unlike non-renewable oil, peak utilization of metal resources cannot be described with a conventional Hubbert Peak Curve because of the steady decline of metal ore grades (Prior et al., 2012) and the high recyclability of metal resources (Mason et al., 2011). However, the Hubbert Peak Curve can be adapted to account for ore grade decline and recycling in characterizing peak mineral utilization. Actually, the original Hubbert curve is a probability density function of a logistic distribution curve (May et al., 2012; Rustad, 2012):

$$\frac{\mathrm{d}\ln Q(t)}{\mathrm{d}t} = s \times \left(1 - \frac{Q(t)}{Q_{tot}}\right) \tag{1}$$

where t is the duration in years (yr), $Q(t)$ is the cumulative production, Q_{tot} is the total amount of the resource available, and s is a parameter that can be interpreted as the initial rate of production at $t = 0$. The annual and cumulative demand for nickel can be calculated by Eq. (1) and the following two equations:

$$D(t)_{\eta} = D(t)_0 - \eta \times D(t - L)_0 \tag{2}$$

$$Q(t) = Q(t - 1) + D(t)_n = \int D(t)\mathrm{d}t \tag{3}$$

where η is the nickel recycling rate (%), which is the quotient of the recycled amount to the generated amount in the same period (Graedel et al., 2011); $D(t)$ is the total annual net nickel demand at t (ton); $D(t)_0$ is the total annual nickel demand at t and the recycling rate of 0% (ton); L is the life span of the product (yr); $D(t\text{-}L)_0$ is the annual nickel demand at $t\text{-}L$ and the recycling rate of 0% (ton); $\eta \times D(t\text{-}L)_0$ is the amount of nickel recoverable from recycling based on an η recycling rate and an outflow of nickel initially put into use in year ($t\text{-}L$) (ton); $Q(t\text{-}1)$ is the cumulative nickel demand at t-1 (ton); and $Q(t)$ is the cumulative nickel demand at t (ton).

2.2.2. S-shaped rules for peak utilization

Previous studies indicate that utilization of metal can enhance gross domestic product (GDP), and S-shaped rules can substantially describe the relationship between per capita utilization of mineral resources and per capita GDP (Fig. S3) (Tilton, 2015; Wang et al., 2010). Since peak utilization cannot be modeled accurately from reserves because of the potential of yet-to-be discovered reserves, S-shaped rules are used to determine the peak utilization of nickel. Therefore, the yearly utilization of nickel in a country or region (e.g., China) can be expressed as

$$d = p \times \gamma = p \times f(\mathrm{GDP}) \tag{4}$$

where d is the yearly utilization of nickel in a region, p is the population, and γ is the per capita nickel utilization, which is a function of per capita GDP (Fig. S3).

2.2.3. Scenario analysis of the increasing rate of nickel utilization and the nickel recycling rate

The carrying capacity for peak minerals is defined as the supporting maximal industrial amount supported by geological ore reserves (Sun et al., 2016; Zeng and Li, 2015). Therefore, the carrying duration of nickel resources is the period to "zero" geological reserves, which will be substantially affected by closed-loop supply with applications and recycling (Wellmer and Hagelüken, 2015). In light of the relationships between cumulative demand for nickel and other related variables (Eq (1)–(3)), the increasing rate of nickel applications and the recycling rate of EoL products can be anticipated by the following two equations:

$$\sum_{t=2012}^{n} D(t)_{\psi,\eta} \leq R + \sum_{t=2012}^{n} I(t) \tag{5}$$

$$\sum_{t=2012}^{n} D(t)_{\psi,\eta} = \int_{2012}^{n} \{683 \times (1+\varphi)^{x-2012} - [683 \times (1+\varphi)^{x-2012-m} - D(t)_0 \times \eta^{x-2012-m}]\}dt \tag{6}$$

where ψ is the annual increase in the rate of nickel applications or utilization (%) based on national statistics of nickel utilization; n is the carrying duration of nickel resources (yr); $D(t)_{\psi,\eta}$ is annual nickel demand at t, ψ and η (t) (kt); R is chosen as 3000 for reserve or 7643 for reserve base in 2014 (kt); 683 is the utilization of nickel in 2012 (kt); m is the lifetime of nickel products (yr); and $I(t)$ is the net imported mineral (kt), which is defined by the linear regression.

3. Results and discussion

3.1. Prediction for nickel demand in China

The stainless steel industry accounts for approximately 40–85% of Chinese nickel demand, followed by electroplating (9–32%), non-ferrous alloys (5–10%), and batteries (3–9%) (Table S3). Nickel demand has been steadily increasing since 1950, driven primarily by rapid industries growth (Fig. S2). Since 2004, the production of stainless steel, batteries, electroplating, non-ferrous alloys, and other nickel-containing products has been growing annually by 115%, 8.3%, 2.8%, 22.8%, and 21.5%, respectively (Tables S3 and S4). It can be attributed to China's flourish of stainless steel industry in recent two decades. The share of China's stainless steel output in global amount has grown from 3% in 2000 to 52% in 2015. And in 2010, China became the net exporter from the net importer (CLII, 2016).

In theory, China is still a developing country so that the linear growth pattern is expected to continue (Text S2). And in practice, the collected historical data in recent years is fit well for the linear regression (See Tables S3 & S6, and Fig. S4). Both theory and practice can indicate a linear growth of nickel utilization from 2009 to 2016 remains in near future of 2017–2030. Despite the current downsizing of the global mining industry, nickel demand in China will reach 2200 kt in 2030—far beyond the national annual production of nickel (Fig. 1A). Among all applications, nickel demand for stainless steel production is expected to rise rapidly from 526 kt in 2011 (77% share of total utilization) to 1171 kt in 2020 (84% share) and finally to 1920 kt in 2030 (86% share) (Fig. 1B). Despite the growth of absolute non-stainless steel applications, including batteries, electroplating, and non-ferrous alloys, their total share in nickel demand is going down from 33% in 2011 to 16% in 2020 and 14% in 2030.

The predicted nickel demand for batteries demonstrates a similar trend with the obsolescence of consumer electronics and electric vehicles (Restrepo et al., 2017). China's 12th Five-Year Plan released by the Ministry of Science and Technology and State Council expects on