Postprint: Medium- and Long-Term Sustainable Supply Pathways for Typical Strategic Metals in China under Carbon Neutrality

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Abstract

Mineral resources are an important material foundation for economic and social development. Irrational extraction, utilization, and consumption not only affect the security of industrial and supply chains, but also cause severe pollution to the ecological environment. The new round of technological revolution and the carbon neutrality strategy are reshaping the global innovation landscape and technological pattern. As China' s economic and social development enters the post-pandemic stage, the supply-demand structure of strategic metals is undergoing profound changes. On the one hand, security challenges facing their industrial and supply chains have spread from the traditional concern over whether resource product acquisition can be guaranteed to the entire industrial chain, including extraction, processing, application, and recycling. On the other hand, the generation of solid waste in China is growing rapidly, but its recycling rate as secondary metals remains low, which will lead to substantial resource losses. Looking to the future, the state (government) should promptly establish a refined classification and grading management system for the resource quantities and reserves of secondary metals, improve the collection and resource recovery system for secondary metals, promote the formulation of systems and standards for efficient resource utilization, ensure efficient internal circulation and self-sufficiency of domestic strategic metals, and completely break away from the situation where strategic metals are constrained by others.

Full Text

Preamble

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Pathways for Medium- and Long-term Sustainable Supply of Typical Strategic Metals in China in Context of Carbon Neutrality

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Abstract

Mineral resources are fundamental materials for economic and social development. Irrational exploration, utilization, and consumption not only undermine the security of industrial chains and supply chains but also cause serious environmental pollution. A new round of technological revolution and the carbon neutrality strategy are reshaping the global innovation landscape and technological structure. As China' s economic and social development enters the post-pandemic era, the supply and demand structure of strategic metals is undergoing profound changes. On one hand, security challenges facing industrial and supply chains have expanded from traditional concerns about resource availability to encompass the entire chain, including extraction, processing, application, and recycling. On the other hand, China' s solid waste generation has grown rapidly, yet the recycling rate of secondary metals remains low, resulting in substantial resource losses. Looking ahead, the government should promptly establish a refined classification and grading management system for the resource volume and reserves of secondary metals, improve the collection and recycling system for secondary metals, and promote the formulation of systems and standards for efficient resource utilization. These measures will ensure efficient internal circulation and self-sufficiency of strategic metals domestically, fundamentally eliminating dependence on foreign sources.

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Strategic metal resources play a decisive role in safeguarding national defense and economic security, and have increasingly become the focus of competition among major powers in development and strategic games. Along with the wave of technological progress and industrial revolution, major countries worldwide have prioritized research on metal criticality to enhance international economic competitiveness and ensure national defense security. The United States, Japan, and the European Union have released critical (or strategic) resource catalogs with dynamic updates over time, while the United Kingdom, India, Australia, and Canada have also published strategic metal resource catalogs in recent years.

1. Substance Flow Analysis Methods and Results

Driven by global carbon peaking and carbon neutrality goals, low-carbon industries centered on low-carbon energy technologies are developing rapidly. These industries consume large quantities of strategic metals such as lithium, cobalt, nickel, gallium, indium, and rare earth elements. However, carbon emissions from the entire lifecycle of metal extraction, utilization, consumption, and recycling account for approximately 10% of global carbon emissions [1,2]. Therefore, establishing sustainable supply pathways for strategic metals under carbon reduction imperatives is urgent. As the world' s largest producer and consumer of metal mineral resources, China' s current strategic mineral catalog is primarily formulated from the perspectives of national defense security, economic security, and the development needs of strategic emerging industries, covering major traditional energy minerals, metal minerals, and non-metal minerals. However, in today' s pursuit of sustainable development, the importance and irreplaceability of strategic metals dominated by rare, dispersed, and rare earth elements are becoming increasingly significant. The 20th Party Congress report proposed, "Consolidate the leading position of advantageous industries, accelerate the filling of gaps in areas related to security development, and enhance the supply guarantee capacity of strategic resources." Strategic metal supply pathways include four aspects: domestic primary resource extraction, foreign primary resource imports, domestic secondary resource recycling, and foreign secondary resource imports. Since August 2017, the implementation of the "foreign waste" import ban has drastically reduced foreign secondary resource imports [3], meaning future supply pathways for strategic metals in China will rely mainly on the first three aspects.

Resource shortages and surging waste volumes are troubling industrial and supply chain security. Research on 23 typical valuable materials in product waste (also known as "urban mining") found that the total amount of 20 secondary resources will exceed industrial demand before 2050, essentially achieving resource self-sufficiency [4]. Meanwhile, resources lost to the environment during extraction, consumption, utilization, and recycling processes. Under current technical and economic conditions, approximately 5%–10% of materials are lost to environmental media during each lifecycle stage, generating solid waste such as tailings and smelting slag or defective products.

1.1 Analysis Methods and Overview

Substance flow analysis is an effective method for studying the metabolism of specific substances (such as metals) within a country or region. Based on a life cycle analysis perspective, this method investigates the flow characteristics of a substance at different life cycle stages, providing important information for sustainable resource and environmental management. Its purpose is to conduct directional and quantitative analysis of material flows and stocks in socio-economic systems, and to implement comprehensive regulation of resource products and waste emissions to achieve the goal of optimizing system resources and energy.

Generally, the material flow process of metal resources proceeds as follows: beneficiation, smelting, and processing to produce semi-finished products for utilization; manufacturing different products for utilization; formation of product waste after consumption; partial waste landfilled and entering the pedosphere; partial waste recycled as secondary metals and fed back into the production and processing process. Throughout the metal flow process, not only are resources and products generated, but substances are also released and waste is produced—almost every stage releases substances into environmental media and generates solid waste such as tailings and smelting slag or defective products (Figure 1a [Figure 1: see original paper]). For China, metals undergo extraction or foreign import, are processed and applied in different products to meet domestic demand, and form product waste after consumption. Waste recycling then becomes an important part of resource supply (Figure 1b).

1.2 Global Substance Flow Data for Typical Strategic Metals

Based on the global substance flow analysis framework and currently available data, this study obtained global substance flow data for metals such as cobalt, indium, and niobium. This data covers the entire process from lithosphere resource extraction, processing and utilization, product manufacturing, and consumption to waste generation and treatment, including information on substance release during the process (Figure 2 [Figure 2: see original paper]).

2. Supply Characteristics of Typical Strategic Metals

2.1 Extraction of Typical Strategic Metals

Since the 20th century, rapid economic growth and urbanization rates have led to substantial increases in global metal mineral extraction and utilization. According to data for 35 metals published by the United States Geological Survey (USGS), the total extraction and smelting volume increased from 73 million tons in 1922 to 1.478 billion tons in 2022—a roughly 20-fold increase. It took approximately 60 years to increase extraction and utilization by 500 million tons starting from 1922, but in recent years, this same increase has taken only 16 years. Clearly, human exploitation of Earth' s resources has accelerated over the past century (Figure 3 [Figure 3: see original paper]). Meanwhile, in 2020, the weight of various products produced by humans globally exceeded the total natural biomass on Earth [11], further evidencing that typical strategic metals are being rapidly consumed.

2.2 Production and Trade of Typical Strategic Metals

(1) Lithium. Lithium metal is essential for promoting low-carbon energy transition and developing strategic emerging industries. China' s lithium extraction has grown from 10,000 tons in 2019 to 26,000 tons in 2021 [12]. From 2015 to 2021, the rapid development of the electric vehicle industry significantly increased China' s lithium demand, resulting in a total of 100,000 tons of lithium entering the refining stage in 2021, with approximately 86% of raw lithium materials relying on imports. The large-scale import of raw lithium materials serves not only to meet domestic demand but also export requirements. Lithium imports have shown fluctuating growth, increasing from 14,000 tons in 2015 to 79,000 tons in 2021, while lithium exports have grown steadily from 11,000 tons to 48,000 tons during the same period.

(2) Cobalt. Over the past two decades, cobalt production has also shown continuous growth. Cobalt mine production had an average annual growth rate of 8% from 1995 to 2021, reaching 170,000 tons in 2021, with most coming from ore extraction. From 1995 to 2021, globally secondary cobalt production accounted for 8.3% of total cobalt supply. The global cobalt supply chain has undergone significant changes in recent decades. China' s primary refined cobalt production maintained rapid growth, increasing from 200 tons in 1995 to 130,000 tons in 2021. Since 2004, China has surpassed Finland to become the world' s largest cobalt producer. Additionally, bilateral trade flows of cobalt products between China and South Korea (20,000 tons) are prominent in the global cobalt product trade network, largely reflecting geopolitical proximity between the two countries.

(3) Indium. Indium is widely used in high-tech and renewable energy industries, with production increasing from 118 tons in 1990 to 926 tons in 2021. Since 2000, China has dominated global primary indium production, accounting for 57% of world production in 2021, and is expected to remain the primary supplier. Indium is typically a by-product of mineral extraction, currently sourced mainly from zinc ores (95%), tin ores (4%), and copper ores (1%). Additionally, indium can be recovered from smoke dust, dust, slag, lead-zinc alloy residues, and lead-tin-zinc smelting (<1% of global indium production). Based on annual production data from Zhang Weibo [13] and other literature, backward estimation of average recovery rates and losses in smelting, beneficiation, and mining processes shows that 9,340 tons of indium metal were produced from 113,000 tons of ore materials worldwide during 2011–2020.

(4) Niobium. Niobium is a key material for developing high technologies including information technology, new energy technology, space technology, biotechnology, and superconductivity technology. Global proven niobium reserves exceed 17 million tons, with Brazil being the world' s largest producer, accounting for 94% of world production in 2021. China' s niobium deposits are generally polymetallic symbiotic deposits with low development and utilization levels, resulting in domestic extraction costs higher than import prices and thus lacking commercial viability. Additionally, niobium metal can be produced as a by-product of other metals, which can effectively reduce costs. Currently, China produces approximately 300 tons of niobium-tantalum concentrate annually [14].

(5) Germanium. Germanium is widely used in high-tech fields such as electronics and optics. China' s retained germanium reserves are approximately 3,500 tons, accounting for 41% of global reserves [15]. Germanium-bearing deposits in China are mainly distributed in Inner Mongolia and Yunnan, primarily occurring in lead-zinc and coal deposits. Major germanium producers include China, the United States, Russia, and Canada, with China being the world' s largest producer, accounting for approximately 67% of global annual production. In 2015, influenced by environmental protection policies and resource protection measures, China's germanium production declined year by year, reducing global annual production from 146 tons in 2015 to 124 tons in 2017. However, in 2018, as global germanium demand increased, China' s annual production rose to 95 tons, increasing global annual production to 130 tons.

3. Consumption Characteristics of Typical Strategic Metals

Based on global substance flow analysis and the latest collected data, this study conducted substance flow analysis for the five strategic metals—lithium, cobalt, indium, niobium, and germanium—regarding their consumption and product waste metabolism in 2021 (Figure 4 [Figure 4: see original paper]).

3.1 Lithium

Since 1996, China has been the world' s largest consumer of lithium metal, accounting for 25% of global consumption. From a consumption sector perspective, before 2015, the main consumption areas globally were glass and ceramics, lithium-based grease preparation, and primary aluminum smelting. After 2015, the rapid development of the electric vehicle industry greatly promoted lithium consumption demand, increasing lithium consumption in the battery sector from 13,000 tons in 2015 to 62,000 tons in 2021, with an average annual growth rate of 30%. In 2021, the battery sector' s share of lithium consumption had grown to 71% [22], with electric vehicle power battery manufacturing becoming the main driver of lithium demand growth.

In 2021, China' s social stock of lithium metal reached 195,000 tons, equivalent to 13% of the country's natural lithium reserves, with an average annual growth rate of 8% from 2015 to 2021. Before 2015, China' s main lithium consumption sectors were ceramics, glass, and laptop computers. Due to the 20-year service life of ceramics and glass, although their share in China' s lithium social stock had dropped to 75% by 2021, they remain the largest consumption sector for lithium social stock. Pure electric vehicles and energy storage systems have shown the fastest growth in lithium social stock, accounting for 17% and 3% of total social stock respectively in 2021. Lithium entering waste after consumption was 12,000 tons in 2021. Non-lithium battery product waste dominated lithium waste before 2019, but its proportion decreased from 87% in 2015 to 51% in 2021. Since 2020, the rapid growth of electric vehicles has made lithium batteries the largest source of lithium waste, with waste lithium batteries accounting for 35% of all lithium waste in 2021. Similar to the trend in lithium demand, lithium scrap will grow rapidly in the coming decades, reaching 110,000 tons, 400,000 tons, and 1.15 million tons in 2030, 2050, and 2080 respectively [23], becoming valuable "urban mining" resources in the future.

3.2 Cobalt

In 2021, global cobalt consumption reached 175,000 tons, with electric vehicles being the main consumption sector at 34%, followed by laptop computers (12%) and mobile phones (11%). Since 2006, the lithium battery industry has surpassed the superalloy industry as the main application sector for cobalt consumption. Analyzing the detailed breakdown of applications of lithium batteries reveals that from 1995 to 2008, cobalt was mainly used in mobile phone manufacturing; in 2009, cobalt usage in laptops exceeded that in mobile phones; and by 2018, electric vehicles had become the most important consumption sector for cobalt. Compared with all types of end products, electric vehicles represent the fastest-growing consumption area for cobalt, with an average annual growth rate of 30% from 2010 to 2021.

Global cobalt in-use stock reached 450,000 tons in 2021, with an average annual growth rate of 11%. In 1996, cobalt applied in superalloys accounted for the largest share of social stock (26%), but by 2015, cobalt in laptops accounted for the highest proportion (29%). In 2021, laptops represented the largest share in cobalt waste product flow (19%), followed by superalloys (16%). From 1995 to 2021, the ratio of total cobalt-containing waste recovered to waste product volume was 0.14, with cobalt recovered from lithium batteries accounting for the largest proportion (46%) of recycled scrap. Over these 26 years, the United States, European Union, and China have remained the main consumption regions for cobalt, with China and the United States accounting for 35% and 12% of global cobalt consumption respectively in 2021.

3.3 Indium

Indium is widely used in electronics and renewable energy industries, primarily for producing indium tin oxide (ITO). From 2010 to 2020, 73.0% of global refined indium production was used for ITO targets, 10.9% for electronic components and semiconductors, 12.7% for solders and alloys, and 3.5% for other products. During ITO manufacturing, only 30% of indium successfully deposits on substrates, while the remaining 70% can be recovered (recovery efficiency >95%). From 2010 to 2020, 839 tons, 156 tons, 154 tons, 139 tons, and 111 tons of indium flowed into LCD TVs, laptop computers, mobile phones, liquid crystal displays (LCDs), and tablet computers respectively. In the electronic components and semiconductor industry, approximately 434 tons of indium were used to produce copper indium gallium selenide (CIGS) panels, and 373 tons for light-emitting diodes (LEDs).

Currently, only 1% of indium-containing waste is formally recycled. Such low recovery rates are mainly due to relatively low indium concentrations, lack of resource recovery technologies, few incentive measures, and the absence of a recycling system for indium-containing waste products. Additionally, from 2010 to 2020, indium losses in LCD TVs, mobile phones, laptops, LCDs, tablet computers, LEDs, and CIGS were 201 tons, 94 tons, 68 tons, 53 tons, 43 tons, 50 tons, and 0.1 tons respectively. The indium in electronic waste has not been recycled, with total indium metal losses amounting to approximately 1,773 tons.

3.4 Niobium

The main niobium product is ferroniobium, with approximately 90% of global niobium used in steel production. Beyond steel, niobium is applied in many cutting-edge technology fields such as superconducting magnets and medical applications. Its processed products are divided into four types: in 2020, standard-grade ferroniobium accounted for 90% of total niobium production; vacuum niobium alloys (such as nickel-niobium) accounted for 3%; niobium metal and its alloys and chemicals each accounted for 3% of total production. The market share proportions of these four products are 22%, 24%, 44%, and 10% respectively, used in oil and gas pipelines, automobiles, steel structures, and stainless steel. Vacuum niobium alloys are used to produce superalloys, niobium metal and alloys for superconductors, and niobium chemicals for functional ceramics and catalysts with market shares of 60% and 40% respectively. These products are subsequently used in heavy infrastructure construction and engineering fields. After products reach end-of-life, the vast majority are landfilled, with only 3% of waste products recycled, mainly from superalloy scrap.

3.5 Germanium

Germanium is mainly used in infrared optics, optical fibers, catalysts, electronics, and solar energy. In 2019, global germanium consumption was 136 tons, with 29% used for optical fiber manufacturing, followed by infrared applications (20%), catalyst manufacturing (17%), and electronics and solar energy (16%). Other applications (such as medicine and phosphor preparation) accounted for 18%. Optical fiber and infrared products have remained the main consumption areas for germanium. Germanium is applied in space solar energy for solar applications, with some involvement in ground photovoltaics, though its application in ground photovoltaics is limited due to high costs. China is a net exporter of germanium metal, with net exports reaching 37 tons in 2007. However, affected by national policy adjustments, exports declined year by year from 2007 to 2015 (from 37 tons to 6 tons), then rebounded after 2016, reaching 17 tons in 2019. China mainly exports intermediate germanium products such as high-purity germanium ingots, germanium single crystals, and infrared germanium lenses. Germanium products have long service lives, such as optical fiber and infrared products exceeding 20 years. In 2019, China' s germanium in-use stock reached 450 tons, with annual waste generation of 9 tons.

4. Assessment of Sustainable Supply Pathways for Typical Strategic Metals

China is currently undergoing profound transformation, and strategic metal supply security strategies must align with the new security concept of "common, comprehensive, cooperative, and sustainable" security and the national governance principle of building a community with a shared future for mankind. The supply capacity of a single mineral resource also significantly impacts the supply status of other mineral resources. Therefore, a holistic perspective is needed to comprehensively consider various factors and seek optimal solutions for strategic metal supply security issues.

(1) Lithium. The electric vehicle industry has increased lithium demand, with total demand projected to reach 1.31 million tons by 2100. However, due to enhanced recovery and recycling capabilities, the growth trend of net demand will reach a turning point before 2100. Nevertheless, recycling will not reverse this trend in the short term [24], and net demand will maintain stable long-term growth. By 2100, global cumulative lithium demand will reach 52.6 million tons, with recycling playing an important role in reducing primary resource demand by 26.5 million tons. Under current technology portfolios, lithium' s net cumulative demand will be 26.1 million tons. With lithium' s economically recoverable reserves maintained at current levels and recycling utilization reaching 100%, secondary resource reserves will exceed primary resource reserves by 2050, becoming the main global lithium supply source. However, due to continued growth in electric vehicle production, lagged battery scrapping, and low recovery rates, lithium will still primarily depend on primary resource supply in the medium to long term.

(2) Cobalt. Similar to lithium, growing cobalt demand will challenge sustainable supply. Under current technology portfolios, total cobalt demand could reach 1 million tons by 2100. Metal recycling will not reverse this trend in the short term, and net demand will maintain stable long-term growth, reaching 260,000 tons by 2100. It should be noted that battery chemistry systems are undergoing rapid development and transformation, with the possibility of rapid development of "cobalt-free" chemistry systems. With the rapid development of nickel-cobalt-aluminum ternary lithium batteries, the ratio of cobalt' s cumulative demand to reserves will reach 112%, indicating a grim prospect for resource sustainable supply.

(3) Indium. Although current indium production meets demand, medium- to long-term availability faces serious challenges. The cumulative indium required for electronics production and manufacturing from 2010 to 2050 is projected at 5,643 tons, while the cumulative indium in electronic waste by 2050 will be 4,068 tons, potentially achieving balance by 2035 under ideal conditions where all indium can be recovered. In renewable energy industries, even under the most conservative scenarios, photovoltaic modules' indium demand exceeds that of all other electronic products. Unlike other indium-containing products, photovoltaic modules have long lifespans (approximately 25 years). Therefore, future indium-containing waste products will become the main source of secondary indium, and the industry urgently needs to develop circular economy approaches to recover indium-containing waste products. Among these, LCD screens and photovoltaic modules will drive future indium demand and generate the most indium-containing waste.

(4) Niobium. Niobium demand will maintain stable growth, driven by three factors: high demand for niobium consumption in structural steel for bridges, buildings, and large construction projects; widespread use of niobium alloys in automobile manufacturing; and development in new technology and military application fields. Currently, the niobium market has an annual growth rate of 2.5%–3.0%. It is estimated that if the niobium recovery rate is 0, approximately 168,000 tons of niobium-containing waste will be lost by 2090, whereas when recovery rates exceed 90%, only about 16,000 tons or less will be lost. To improve niobium' s sustainable utilization, the government should optimize niobium consumption patterns and control niobium flows by implementing circular economy action plans across entire industries.

(5) Germanium. The infrared optics and optical fiber industries have promoted germanium consumption while creating supply risks. Over the past decade, germanium consumption has grown rapidly and is projected to reach 150 tons by 2050, with China potentially facing a germanium supply crisis from 2030 onward. Even if germanium production remains at the current level of 100 tons per year, current reserves will only last until 2035. Meanwhile, China's recycling industry chain for germanium waste products is immature and small-scale. If full recovery of germanium waste products can be achieved, 1,000 tons could be recovered by 2050. Nevertheless, end-of-life recycling cannot solve germanium shortages, and governments and enterprises must simultaneously strengthen the secondary metal recycling industry chain, find germanium substitutes, and increase germanium exploration efforts to address sustainable supply issues.

5. Conclusions and Recommendations

China' s domestic strategic metal supply still relies on primary resource extraction and smelting, while secondary resource recycling can help reduce dependence on underground resources and foreign imports. Therefore, it is essential to coordinate primary and secondary resources, revitalize secondary resources, and form sustainable supply pathways. Specific policy recommendations for different types of strategic metals are as follows.

(1) Expand sources and reduce consumption; conduct orderly and measured extraction and utilization of primary metal resources. Considering the supply risks and pathways of lithium, indium, and niobium, and given the shortage and high foreign dependence of strategic metals such as lithium and cobalt, continued exploration for new mineral deposits is needed to increase proven metal resources and improve extraction and smelting technologies to reduce metal losses. For niobium, which China is extremely short of, it is necessary to find international import sources while urgently developing new technologies to "break the metal chokehold" through product technology revolutions, reducing the use of strategic metals with high shortage and foreign dependence and changing the industrial demand pattern. For strategic metals such as germanium and indium where China has abundant reserves, protection policies should be established for orderly and measured extraction and utilization.

(2) Establish a refined classification and grading system for secondary resource volume and reserves, and promote the formulation of systems and standards for efficient metal utilization. It is recommended that the National Development and Reform Commission, Ministry of Ecology and Environment, and Ministry of Natural Resources jointly lead the development of classification and grading standards, coordinate resource governance, accurately account for various secondary metal outputs in China, clarify the regional distribution of secondary metals, and create classification and grading maps of reserves and resources. The focus should shift from primary resource development to collaborative development of primary and secondary resources as the core, achieving orderly and measured use of various resources to ensure China' s metal supply security.

(3) Comprehensively improve the regional collection system for secondary metals and promote efficient internal circulation of domestic resources. For strategic metals such as lithium, cobalt, indium, and niobium that China is short of and highly dependent on foreign sources, secondary resources in China can gradually meet industrial development needs. To address low collection rates of secondary metals, the government should deepen the Extended Producer Responsibility system to cover the entire industrial chain, scientifically delineate stakeholder responsibilities, formulate incentive policies such as "trade-in 3.0," fully collect various waste products under legal guarantees to ensure secondary metals enter the recycling chain, and upgrade resource recovery equipment technologies to guide the formation of closed-loop industrial cycles.

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Note: Figure translations are in progress. See original paper for figures.