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Refining the understanding of China's tungsten dominance with dynamic material cycle analysis

Linbin Tang[a,b,c], Peng Wang[a,b,*], Thomas E. Graedel[d], Stefan Pauliuk[e], Keying Xiang[a,b], Yan Ren[a,b,*], Wei-Qiang Chen[a,b,c]

[a] Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, 1799 Jimei Road, Xiamen, Fujian 361021, China
[b] Fujian Innovation Academy, Chinese Academy of Sciences, 1799 Jimei Road, Xiamen, Fujian 361021, China
[c] University of Chinese Academy of Sciences, No.19(A) Yuquan Road, Beijing 100049, China
[d] Center for Industrial Ecology, School of Forestry & Environmental Studies, Yale University, New Haven, CT 06511, USA
[e] Industrial Ecology Group, Faculty of Environment and Natural Resources, University of Freiburg, Tennenbacher Strasse 4, D-79106, Freiburg, Germany

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ABSTRACT

Tungsten is deemed a critical raw material by many nations, given its irreplaceable use in industrial and military applications. In particular, much concern has been drawn to China's high share in global tungsten supply. While various studies have focused on the criticality of tungsten, few have specifically explored how tungsten is produced, consumed, and traded. In this paper, the dynamic material flow analysis is applied to quantify China's annual tungsten cycle from 1949 – 2017. It is estimated that total tungsten mined from ores in China over the past 68-year period is ~2500 kilo-tons (kt). Among those, ~750 kt of tungsten has been exported to other countries, and around 970 kt tungsten is domestically consumed. It is noted ≈1720 kt has been lost from mining, production, and end-of-life stage, and merely ~130 kt has been recycled as end-of-life scrap. Our material flow analysis further refined China's tungsten dominance. Although China currently dominates the global production of tungsten, this dominance will not extend too far into the future given China's limited share of world tungsten reserves and its declining ore quality. Our trade flow analysis reveals that China imported ~35 kt of high value-added downstream tungsten products from outside manufacturers, whose mineral resource was originally imported from China. At present, China by itself is experiencing overcapacity issues in the primary production, which discourages the recycling of at end-of-life (EoL) stage and makes the EoL recycling rate only 10%. It is noted that the percentage of Chinese tungsten for domestic consumption has been increasing in the past few years. This highlights the need for systematic measures from stakeholders along the tungsten cycle to promote sustainable practices for efficient tungsten production, use, and recycling in China. Meanwhile, the results also suggest the importance of monitoring the criticality of tungsten and other critical minerals from a dynamic and material cycle perspective.

1. Introduction

Modern society increasingly relies on metals, especially critical metals that play essential roles in defense, high-technology, and low-carbon applications (Erdmann and Graedel, 2011; Graedel et al., 2015a,b). However, most critical metals are naturally scarce and geographical dispersed, and such a contradiction between resource supply and demand surge has aroused widespread attention from global stakeholders. Tungsten is viewed as critical metal by the European Union, the United States, and other nations (European Commision, 2014, 2018; Mudd et al., 2019; NSTC, 2018) because of its high technology importance and supply instability (Fortier et al., 2018; Moll, 2016). It plays an irreplaceable role in transportation, manufacturing industries, and military due to its unique properties such as high melting point, high hardness, and good conductivity, etc. (Schmidt, 2012; Stafford, 1988). However, the global tungsten reserve is concentrated in only a few countries, such as China, Congo, and Russia. In particular, China holds 58% of the world's tungsten reserve and supplies around 85% of the world's tungsten, which is also partly a reason that some countries regarded global tungsten supply at risk. However, does China really dominate the global tungsten market?

The material dominance is typically deduced by material criticality studies based on some indicators (Erdmann and Graedel, 2011; Graedel and Reck, 2016; Hayes and McCullough, 2018; Helbig et al.,

* Corresponding authors.
E-mail addresses: pwang@iue.ac.cn (P. Wang), yanren@iue.ac.cn (Y. Ren), wqchen@iue.ac.cn (W.-Q. Chen).

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2016; Schrijvers et al., 2020). In 2007, the U.S. National Research Council (2007) proposed a two-dimension matrix to assess material criticality. This approach has been widely adopted in many criticality studies (Bustamante et al., 2018; European Commision, 2014, 2018; Friedman et al., 2012; Glöser et al., 2015; Graedel et al., 2015a,b; Bastein and Rieveld, 2015). Despite the difference in specific indicators used, many of these studies use the concentration of existing production capacities as the primary determinant of supply risk (Graedel and Reck, 2016; Ioannidou et al., 2019). Moreover, most studies treated the material system as a “black box”. However, criticality is a dynamic state relates to a mineral's whole supply system (Bradshaw et al., 2013), which calls for an in-depth analysis of material uses along its life cycle from mining, production, use to endoflife as well as trade linkage with other nations. In order to explore the role of China in the global tungsten supply chain, it is crucial to trace China's tungsten stocks and flows from the perspective of material life cycle.

Material flow analysis (MFA) has been widely used to track the fate of metals along their whole life cycles in a given system (Ayres, 1995; Brunner, 2002). MFA studies are abundant on tracing the critical materials stocks and flows with national and global boundaries, such as cobalt (Chen et al., 2019; Mudd et al., 2013; Nansai et al., 2014), molybdenum (Nakajima et al., 2013), lithium (Sun et al., 2017; Ziemann et al., 2012), rare earth elements (Ciacci et al., 2019a; Du and Graedel, 2011; Rademaker et al., 2013; Swain et al., 2015), indium (Ciacci et al., 2019b; Werner et al., 2018, 2015; Yoshimura et al., 2012), tantalum (Deetman et al., 2018; Nassar, 2017), gallium (Løvik et al., 2015; Meylan et al., 2017), and platinum (Nassar, 2013; Sverdrup and Ragnarsdottir, 2016). However, material flow analysis of tungsten has only been conducted at the global and the USA country level. The earliest MFA of tungsten was conducted by Smith from the U.S. Geological Survey (USGS) that developed the first tungsten flow model and quantified the flows of tungsten in the USA (Smith, 1994). Subsequently, Harper and Graedel used tungsten as an example to explore the end-sector-model (EUSM) and the final-product-model (FPM) to analyze metal flows at the national level (Harper, 2008). Based on this framework, a dynamic material flows analysis of tungsten in the United States from 1975 to 2000 was conducted (Harper and Graedel, 2008). Leal-Ayala et al. traced tungsten flows at the global level using a static MFA model (Leal-Ayala et al., 2015). However, although tungsten is mainly produced in China, an MFA with a specific focus on China has not been conducted yet.

To build the quantitative knowledge base of tungsten stocks and flows, we apply dynamic MFA method to trace the tungsten stocks and flows in China from 1949 to 2017 along its life cycle from mining, through to production, manufacturing, use, and the endoflife (Džubur et al., 2017; Graedel, 2019; Müller et al., 2014). The detailed methods and data are explained in Section 2. Section 3 provides an overview of China's tungsten stocks and flows and the details of production, trade, and recycling. Moreover, to reveal China's contribution in each stage of the global tungsten supply chain, we analyze the representations of China's tungsten industry annually to identify the influential factors behind the different flows and processes. Section 4 provides a detailed discussion of our findings on the challenges to China's tungsten industry in raw material supply, trade pattern, overcapacity in production, and recycling. The final section summarizes the contributions and provides an outlook of future work.

2. Materials and methods

2.1. Scope and system boundaries

The system boundary of this study is mapped in Fig. 1. The spatial boundary is mainland China, while the temporal boundary is 1949–2017. Notably, all flow values are measured by tungsten content.

The life cycle of tungsten in the anthroposphere is comprised of six principal life stages, and the details of them are provided in the Supplementary Materials (SM). The main features of those six stages are described as follows:

2.1.1. Mining

Ore mining and beneficiation are referred to as the Mining stage. The material cycle starts with the extraction of tungsten ores from natural stocks in mineral deposits. Tungsten ores are crushed, grounded, and concentrated by a combination of gravity separation, flotation, and/or magnetic processing steps (Stafford, 1988) to produce the concentrate containing 50%–70% tungsten trioxide (WO_3). In this study, the average content of WO_3 in tungsten concentrate is assumed to be 65%.

2.1.2. Production

The tungsten concentrates are processed for the production of two products: ammonium para tungstate (APT) and ferrotungsten. APT is the most commonly used raw material to form tungsten compound, tungsten metal powder, and tungsten carbides powders. Ferrotungsten is a master alloy used in the production of steel. It can be made using either carbothermic or carbothermic-silicothermic reduction. Tungsten scrap can also be reused as raw materials to make ferrotungsten.

2.1.3. Fabrication

After the production stage, semi products are further processed into metal products, which can be divided into four types: cemented carbides, tungsten mill products, tungsten chemicals, as well as steels and its alloys. Cemented carbides are used for cutting, drilling, and wear-resistant parts of coatings (Schubert et al., 2010). Tungsten mill products are used for electrical and electronic applications (e.g., electronic circuit interconnectors, discharge lighting electrodes, etc.) in the forms of tungsten wire, sheets, and rods (Gunn, 2014). Tungsten chemicals can be used as a coloring agent in the porcelain industry or catalysts, phosphors, and absorbent gels (Sato et al., 2015; Christian et al., 2011; Weil and Schubert, 2013). Tungsten is also one of the most important alloying elements for high-speed steel and superalloy, which are widely used in cutting tools, hard-metal cutting machines, and industrial gas turbines (Jones et al., 2017).

2.1.4. Manufacturing

In this stage, metal products are used by six end-use sectors: Cutting Tools, Machinery & Equipment, Consumer Durables, Electricals, Chemicals, and Others (i.e., cutting tools, electrode, lighting, mobile phone vibrator, pigment, and catalysis, etc.), according to the definitions from International Tungsten Industry Association (ITIA) (Moll, 2016; Zeiler, 2018).

2.1.5. Use phase

Tungsten enters the use phase in the form of final products, which can be grouped into six end-use sectors. Tungsten-containing products remain in anthroposphere to form the in-use stocks until their lifetime expires, with lifetimes varying from one year to decades depending on their product types (e.g., Chemicals, Machinery & Equipment).

2.1.6. Waste management

The discarded final products reaching their ends of life are processed in the waste management stage. This stage includes three options: recycling, incineration, and landfilling (Shedd, 2011). As for recycling options, part of recyclable tungsten end-of-life products are collected, separated, and treated by chemical recycling (hydrometallurgy) and the zinc process to obtain the APT or tungsten metal powder.

2.2. Equations and data

This section depicts methods and data for determining the flows and stocks of tungsten cycles. Generally speaking, the total flows entering

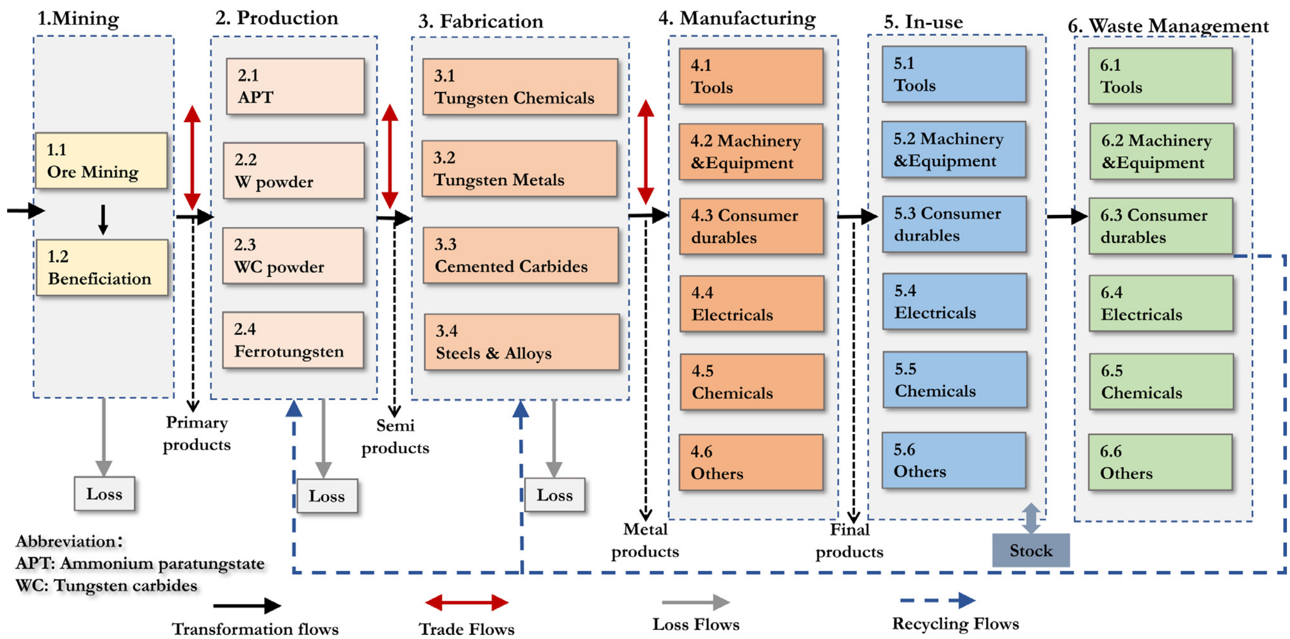

Fig. 1. Framework of tungsten stocks and flows analysis in mainland China (the mining stage is where the tungsten ores are mined and beneficiated to tungsten concentrates. Production, fabrication, and manufacturing stages are comprised of the transformation from the tungsten concentrates through semi and metal products to final products. The in-use stage is where final products are employed, after which the products are discarded into the waste management and recycling system)

each stage equal to the total flows leaving it, as explained by the following equation:

$$F_{W,i,j}^{input} + F_{W,i,j}^{import} = F_{W,i,j}^{output} + F_{W,i,j}^{export} + F_{W,i,j}^{loss} \quad (1)$$

where i is the index for each life stages, j is the index for each year from 1949 to 2017, $F_{W,i,j}^{input}$ is the tungsten contained in material flows demanded by life stage i in year j; $F_{W,i,j}^{import}$ is the import of tungsten embedded in tungsten-contained commodities from stage i for year j; $F_{W,i,j}^{export}$ is the export of tungsten embedded in tungsten-contained commodities from stage i for year j; $F_{W,i,j}^{loss}$ is the quantity losses of tungsten in life stage i for year j; and $F_{W,i,j}^{output}$ is the tungsten contained in final products generated from stage i in year j.

According to Fig. 1, the flows and stocks are classified into four major types with different quantification methods:

2.2.1. *Tungsten transformation flows and losses*

They include tungsten from natural ores deposits through final products to endoflife discards. The incoming flows mostly rely on the direct calculation that multiplies the production data by tungsten contents. In the case of lacking data, the calculation is conducted by combining existing statists with coefficients. The production data are obtained from the governmental and industrial information, such as publications from China Nonferrous Metals Industry Association (CNMIA), International Tungsten Industry Association (ITIA), and Chinese Tungsten Industry Association (CTIA). The data of tungsten contents are obtained from research reports (Smith, 1994; Shedd, 2011), research papers (Fitzpatrick et al., 2015; Harper, 2008), and expert interviews. Processing losses in each life process are estimated based on the production data and the technical transfer coefficients except for the end-use sectors (see the SM for details).

2.2.2. *Tungsten-containing products trade flows*

Owing to the availability of data, we only considered the trade flows after 1980. A list of traded products is identified according to the life cycle framework of tungsten (detailed in the SM). Most trade flows are directly calculated by multiplying the mass of traded tungsten-containing products by their average tungsten contents. The trade data are obtained from the United Nations Trade Database (6-digit HS code) and the China Customs Statistics Yearbook (8-digit HS code).

2.2.3. *In-use stock*

In-use stock refers to the volume of minerals accumulated in the anthroposphere in the forms of final products (Gerst and Graedel, 2008; Kapur and Graedel, 2006). The change of in-use stock is derived from the balance between input and output flows:

$$\Delta S_{EU,\,j,t}^{inuse} = F_{EU,j,t}^{input} - F_{EU,j,t}^{output} \quad (2)$$

$$F_{EU,j,t}^{output} = \sum_{m} F_{EU,j-m,t}^{input} \times P_{m,t} \quad (3)$$

$$\Delta S_{EU,\,j}^{inuse} = \sum_{t} \Delta S_{EU,\,j,t}^{inuse} \quad (4)$$

where $F_{EU,j,t}^{output}$ represents the obsolete tungsten entering the waste management stage, $F_{EU,j-m,t}^{input}$ is the flow of tungsten in final products entering the end-use EU stage in the year *(j-m)*. $P_{m,\,t}$ is calculated by using Normal lifetime distribution models (Melo, 1999) based on the mean and standard deviation of lifetime for six end-use sectors. $\Delta S_{EU,\,j,t}^{inuse}$ and $\Delta S_{EU,\,j}^{inuse}$ are calculated by the mass conservation between inputs into and outputs out of the EU stage.

2.2.4. *Recycling flows*

Due to the lack of statistical data regarding the recycling rate of end-of-life tungsten products in China, we estimated such value based on the end-of-life product waste (in tungsten content) generation and the demand of recycled tungsten products as resource for production. To be more specific, we quantified the input and output of the production and fabrication stage, identified the gap where the input from the primary resource is less than the output, and inferred this gap as the output (i.e. recycled end-of-life scrap) from the recycling stage according to the mass balance principle.

2.3. *Limitations and uncertainties*

Similar to other MFA studies, there are limitations and uncertainties in our results, mainly attributed to the quantification framework and data availability (Izard and Müller, 2010; Laner et al., 2014).

Although the stocks and flows framework (STAF) is widely applied to trace the material's flows in a given boundary (Chen et al., 2016), it may bring some limitations and uncertainties. For example, due to the variety of products and low tungsten content, the tungsten's flows which enter each in-use products are not tracked. Instead, they are integrated into in-use sectors such as tools, electricals, and chemicals. Besides, due to the lack of reliable data, it is not feasible to cover all flows associated with tungsten's activities in China (e.g., those flows where tungsten concentrates are directly used to produce tungsten carbide powder and as additives into steels and alloys without intermediate processes).

Meanwhile, the calculation of this dynamic model requires a significant amount of data from various sources, including the time-dependent statistics and local technical parameters. However, data availability for China's tungsten cycle is limited. As a result, we use the methods of back-calculation and mass balance to make a reasonable estimation of flows in the case of lacking data. Despite the above limitations and uncertainties, this paper has conducted a relatively comprehensive analysis with a substantial contribution to the understanding of tungsten cycles in China. It provides a reference for revisiting China's status in the global tungsten supply chain and the criticality of tungsten.

3. Results

3.1. Overview

Fig. 2 (a) presents China's tungsten stocks and flows along its life cycle from 1949 to 2017. The total tungsten ores mined in China were around 2550 kilo-tons (kt), with 25% of them lost in tailings, and the total production of tungsten concentrates was 1950 kt. Around 750 kt (35% of all concentrates) had been exported to other countries in various forms of products, while about 973 kt tungsten was consumed domestically. It is estimated that 302 kt tungsten still accumulates in the in-use stock, and 1720 kt has been lost to the environment. Besides, around 132 kt of endoflife products are recycled as old scraps with a recycling rate of about 10%. Over more than sixty years, the scale of tungsten cycles has grown significantly with rapid changes in the structure of the tungsten industry. On one hand, domestic mining production shows a 42-fold growth from 1949 to 2017. China became the global factory of tungsten and exported 21 kt tungsten-containing products in 2017 due to the expansion of domestic tungsten production (Fig. 2 (b,c)). On the other hand, compared to 1949, the cemented carbides has replaced tungsten mill products and steels as the primary usage of tungsten in 2017.

3.2. China's changing role in the global tungsten supply chain

Apart from meeting the domestic demand, China exports various forms of tungsten products to the world. As Fig. 2 (a) depicts, China is a net-exporter of tungsten products from 1980 to 2017 and has exported about 35% of tungsten to other countries. China's tungsten export is shipped to almost 200 different countries, most of which are developed economies (Fig. 4). Japan is the largest importer (167 kt), followed by the USA (131 kt) and Korea (86 kt). However, although China has always maintained its roles as a net-exporter of tungsten from the whole life cycle perspective, the composition of its exports has changed considerably. Among the 1980s, China was a net exporter of primary tungsten products. Since the 1992, Chinese government has started to implement a series of restrictions on the extraction and export of tungsten minerals. Consequently, the role of China in global tungsten supply chain has been changed: China has gradually become a net importer of oversea tungsten minerals to compensate the mineral gap constrained by production quota. Meanwhile, given the export quota is only targeted at the export of primary products rather than down-stream products, many nations have imported various down-stream products, shifting China as the net-exporter of down-stream tungsten products (semi and metal products) (Fig. 3 (b)). Therefore, from the whole life cycle perspective, China is not only a tungsten mineral net-exporter but also a global factory of tungsten. China imports raw material of tungsten while exports large amounts of semi products and metal products (Fig. 3 (b)).

3.3. China's tungsten production shifts from export-driven to domestic demand-driven

Fig. 5 depicts tungsten production and consumption in China. It is clearly shown that China was a small tungsten producer before the 1980s, and all tungsten was used to meet domestic demand, in which about 60% of tungsten was directly used as alloy additives for steels or alloys (Fig. 5). From 1980 onwards, the production of tungsten increased significantly, driven by the surge in exports (Fig. 5 (a)). The volume of tungsten export reached 32 kt in 1996, which accounts for about 80% of total production. However, the domestic demand for tungsten has increased sharply since 2000, which has been driven by carbides production (Fig. 5 (a)) and has become the main driver of China's tungsten production growth. It is worth noting that this trend has also appeared on other critical materials in China, such as rare earths (Mancheri et al., 2019). Recently, the rapid development of China's economy has led to the increasing domestic demand for tungsten carbides in transportation, industrial, and infrastructure construction. The domestic tungsten consumption increased to 58.7 kt in 2017, which is about 55 times of that in 1949. Moreover, to construct its manufacturing and high-tech industry base, China has an increasing demand for various high value-added tungsten products (Konyashin and Klyachko, 2013). As shown in Fig. 5 (b), the tungsten carbide products have become the main application (i.e., nearly 60% in 2017), while the share and amount as additives in steel products keeps shrinking.

3.4. End-of-life products can meet half of China's domestic tungsten demand but are not efficiently recycled

After the manufacturing stage, tungsten enters the in-use sectors as in-use material stocks. As shown in Fig. 6 (a), the Tools sector has always been the essential end-use sector for tungsten. It accounted for more than 70% of tungsten consumption before 1985. Then the share of the Machinery and Equipment sector in total inflows kept increasing because of the demand from China's industrial use. Meanwhile, as shown in Fig. 6 (c,d), in-use tungsten stocks have increased rapidly after 1992 and reached around 300 kt in 2017. This increase is mainly driven by the Machinery and Equipment sector (M&E) which has a relatively long lifespan (about 10 years). The amounts of outflows from different end-use sectors to end-of-life (EoL) are determined by the composition of inflows and the average lifespans of end-use products. With the increase of domestic tungsten consumption, the amount of tungsten scrap generation has been increased synchronously. Compared with 3.2 kt in 1950, the amount of tungsten scrap generation reached 27 kt in 2017 (Fig. 6 (b)). Notably, the share of the Tools sector in total scrap generation was largest (more than 60%, Fig. 6 (b)) because of its short lifespan (less than one year) and the relatively large input. Although the amount of tungsten scrap has been equal to half of the domestic demand in the same year (Fig. 5), China's waste management system of tungsten is far from making EoL tungsten efficiently recycled, given that the estimated recycling rate is only around 10%. The considerable amounts of available tungsten old scrap are likely to be the main raw material for China's tungsten production in the future because the tungsten's recycling rate can reach as high as 91% according to estimation from (Ciacci et al., 2015).

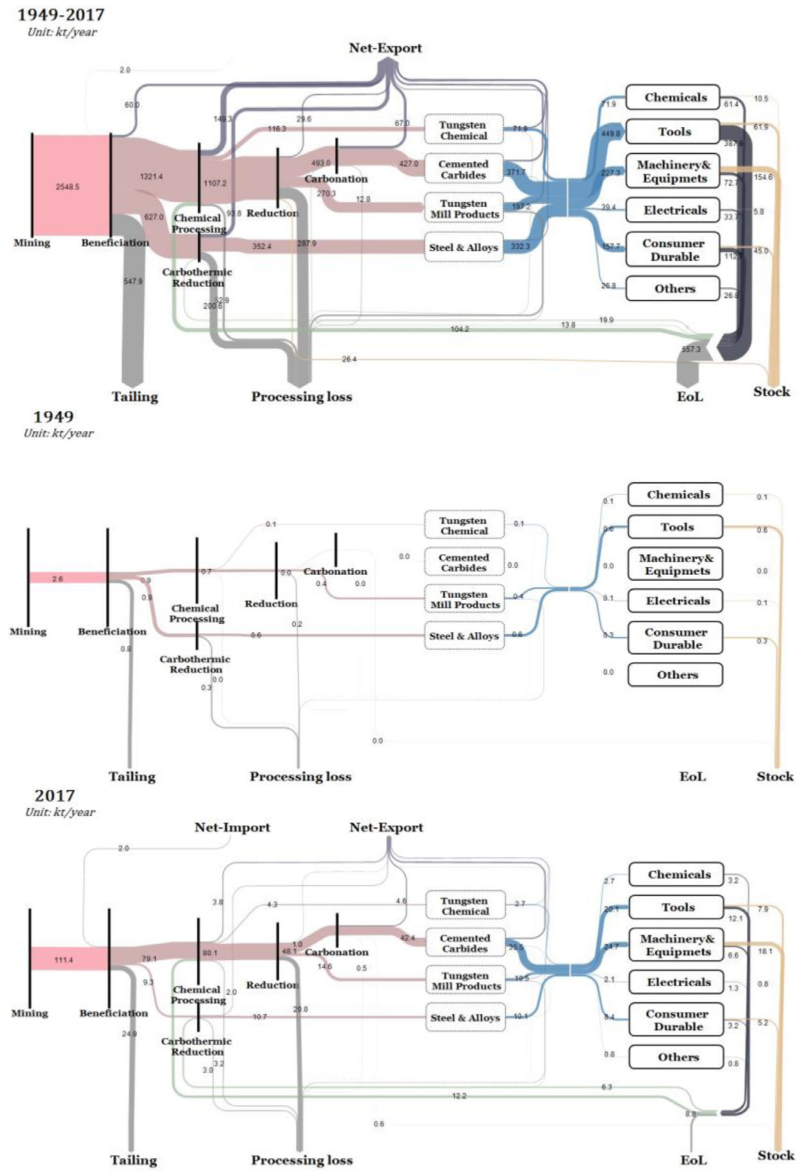

Fig. 2. China's tungsten stocks and flows: 1949–2017 (a); 1949 (b); and 2017(c) (All flows are accumulated to present the overall tungsten use in China during the past sixties years in (a), flows in (b) and (c) demonstrates China's tungsten use in 1949 and 2017; the width of the edge represents the weight of each material flow in the specific temporal boundary; the color of flows differentiates the different stages in tungsten's life cycle; the Eol represents end-of-life tungsten products. The visualization tool is e!Sankey).

4. Discussion

4.1. Revisiting China's dominance over global raw tungsten supply in the long run

China is considered to dominate the global raw tungsten supply mainly because it is responsible for approximately 85% of the world's supply. To question this argument, this study provides an in-depth analysis of China's "tungsten dominance". First, China has a relatively smaller proportion (i.e., 58%) of global tungsten reserve. If the present demand continues, the measured tungsten reserves in China are estimated to be depleted within 30 years (i.e., the volume of demand and reserves are based on the data in 2017). Second, Although the tungsten reserves in China may rise dynamically as new resources become economically and technically viable to extract, the grade of tungsten ores is declining in China (Fig. 7 (b)). The present mined tungsten ore type in China is wolframite that can be extracted and processed efficiently (Stafford, 1988), but it is already depleting. Besides, 70% of China's tungsten reserves are scheelite, a type of ore with lower grade compared to wolframite, of which the mining may cause more massive energy consumption, intensified environmental pollution, and higher operational cost. Consequently, further tungsten mining activities in China will largely be constrained by limited tungsten availability and ore quality declining. This may further weaken China's capacity of global raw tungsten supply. Notably, China has started to import tungsten ore from nations. With the ongoing decline in domestic ore quality as well as the increase in domestic demand, China is expected to have a higher reliance on the oversea mineral resource. Thus, current criticality studies such as (European Commission, 2018; Mudd et al., 2019) may exaggerate the long-term sustainability of China's dominance on the production of tungsten raw materials, which could induce unnecessary panic.

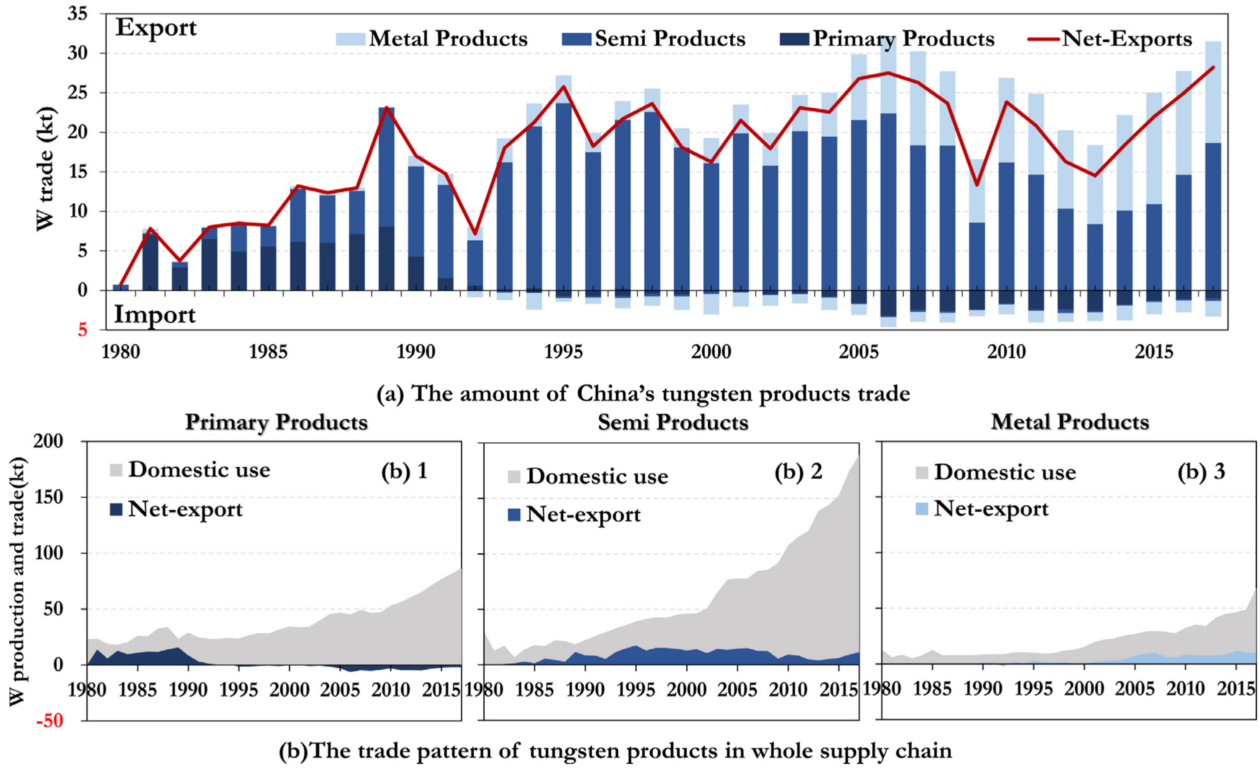

Fig. 3. The amount of China's tungsten products trade (a). The trade pattern of tungsten products in the whole supply chain (b). *(Data source: UN Comtrade. Fig.3(a) shows the import and export volume of tungsten products. The black number indicates exports, while the red number indicates imports. Fig. 3(b) presents the trade pattern changes for ((b) 1) primary products, ((b) 2) semi products, and ((b) 3) metal products. The gray part represents the share of domestic use in China's tungsten production, and the blue part represents the share of net-export in China's tungsten production.)*

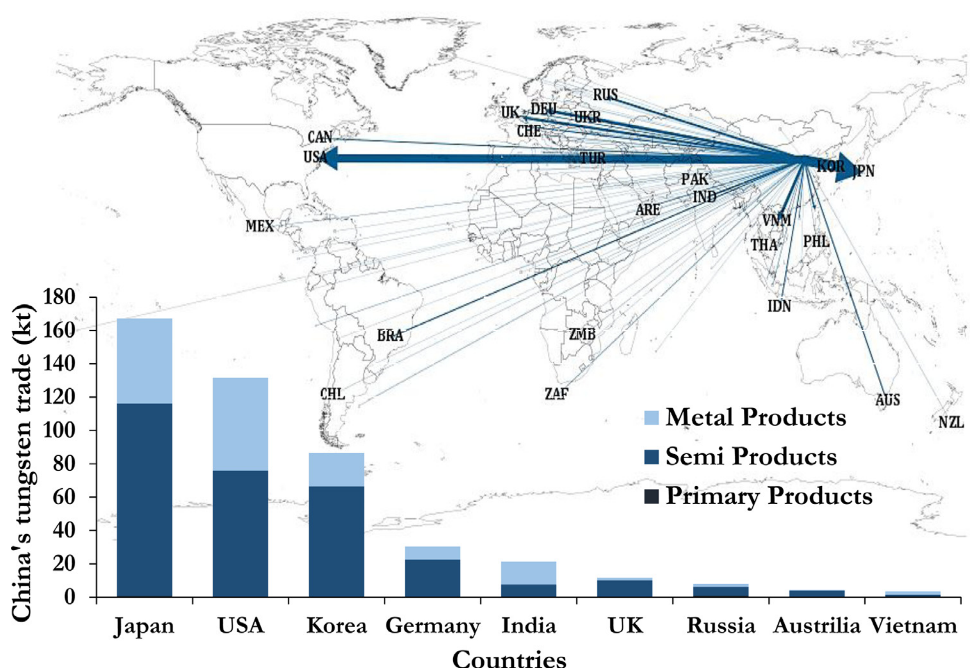

Fig. 4. Key importers of China's tungsten products *(The width of edges represents the trade weight. The direction of edges represents the trade flow. The bars represent the top 9 importers of China's tungsten)*

4.2. China's high dependence on developed countries for tech-intensive tungsten products

In the era of globalization, each nation has a unique role in the global supply chain according to its comparative advantage on resource and technology endowment (Nansai et al., 2014; Papp, 2014). In general, the mining and processing stage is highly resource-intensive with substantial environmental impacts and low technical barriers. While the downstream stages, such as material design and product manufacturing, are characterized by high value-added and high-tech barriers

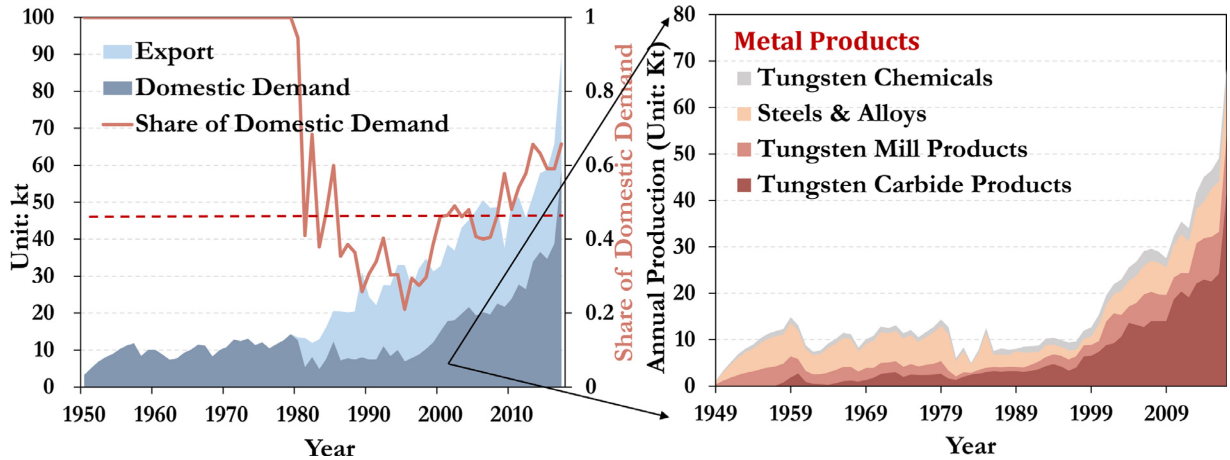

Fig. 5. The amount and composition of China's tungsten production and consumption during 1949–2017 (Fig. (a) represents China's tungsten concentrates use from 1949 to 2017. Domestic consumption of tungsten concentrates is colored in the dark blue, the tungsten concentrates used in export is marked in light blue, and the line represents the share of domestic use in China's total tungsten consumption. Fig.(b) represents the composition of domestic tungsten consumption by applications from 1980 to 2017.)

(Fig. 7 (a)). This paper shows that China has a high share in the mining and processing stage that produces various low value-added and high resource-intensive tungsten products. While its share of the production of tech-intensive final high-end products is relatively meager. Although China is a net-exporter of tungsten products, it still has a high dependence on developed countries for those tech-intensive products. For instance, China accounts for more than 40% of the production in global cemented carbide industry, but 80% of its high-end cemented carbide products rely on imports (CITIC, 2018) from developed countries, including Japan, Sweden, and Korea (Fig. 7 (c)). Yet notably, raw materials for producing high-end products in these nations are mainly imported from China. Therefore, it can also be considered that China indirectly supplies high-end products to the world in the form of raw materials.

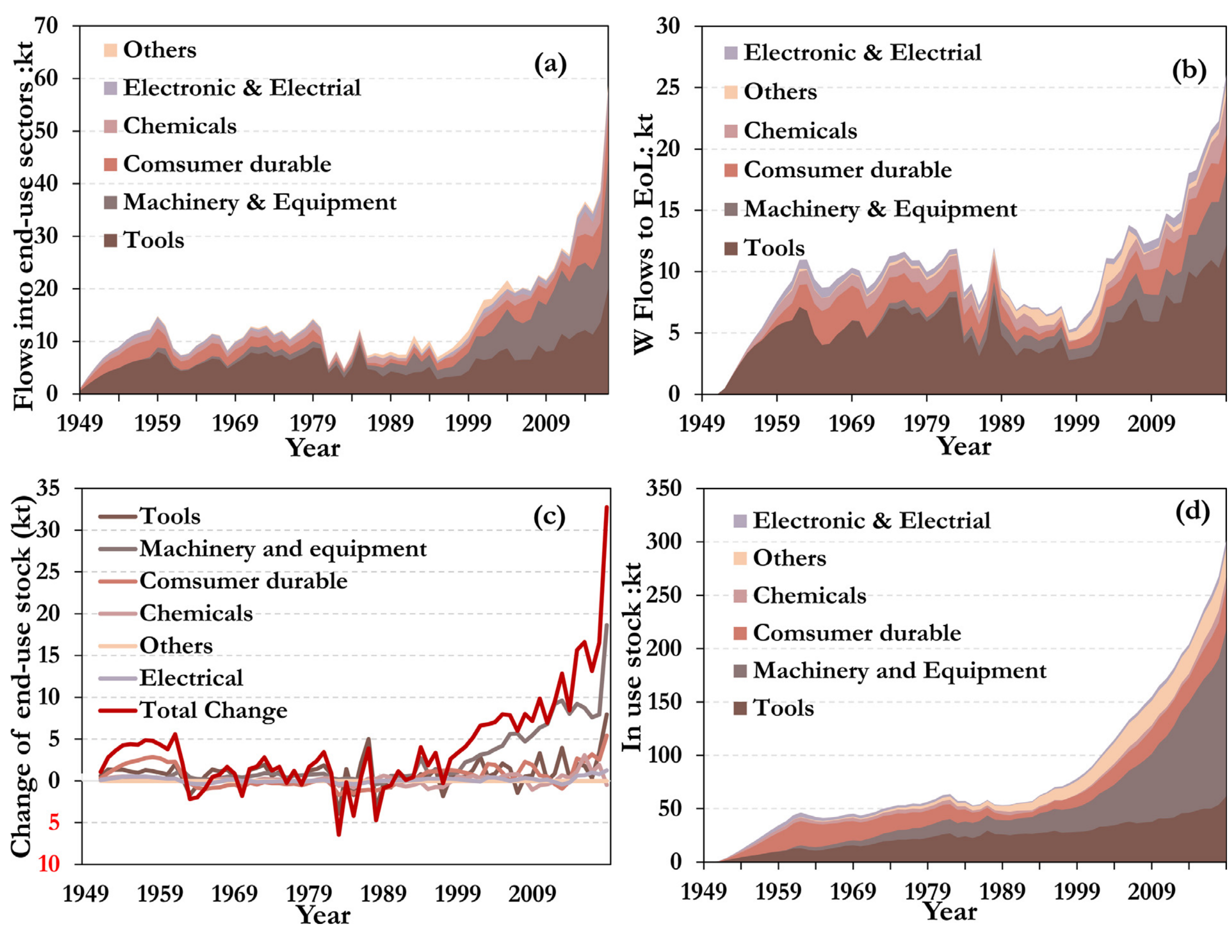

Fig. 6. Stocks and flows of tungsten during the in-use and end-of-life stage in China from 1949 to 2017 ((a) tungsten in-flows to end-use sectors; (b) outflow from in-use stock to EoL; (c) change of in-use stock by end-use sectors; (d)otal in-use stock).

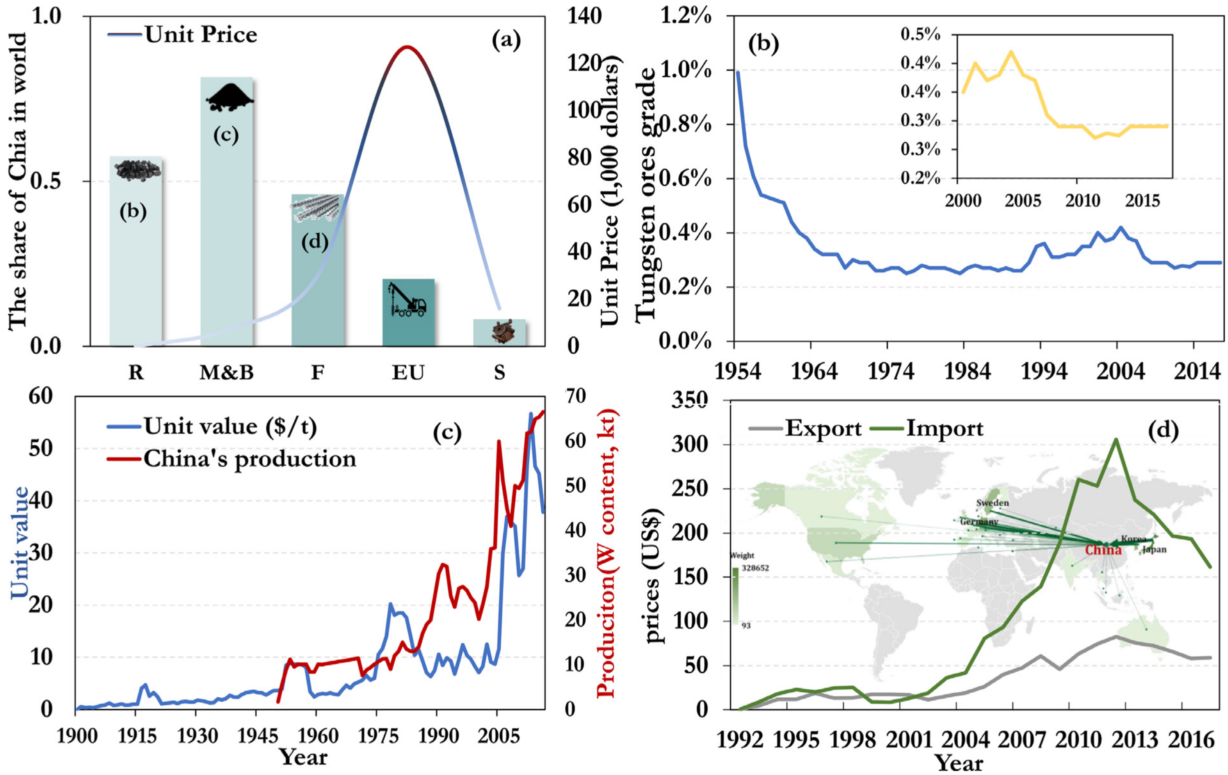

Fig. 7. The status quo of China's tungsten industry and issues in each stage. (a) The share of China in the global tungsten production chain. China has a high share in the R, M&B, and F stage, which produce various low value-added and high resource-intensive tungsten products, but still facing challenges in those stages. *(The bars mean the share of China's production in total global production, and the change of bar color represents the value of the product. Light color represents the low value, while dark color represents the high value. R: reserves; M&B: mining and beneficiation; F: fabrication; EU: end-use products; S: tungsten scrap.)*; (b) In R stage: the declining trend in China's tungsten ores grades *(the blue line)*; (c) In M&B stage: the interaction effect between international tungsten prices *(the blue line)* and China's tungsten production *(the red line)*; (d) In F stage: the trade of cemented carbides in China as a case for China's dependence on developed countries for high-end tungsten-containing products. *(the green line represents imports, and the gray line represents export. Customs code: 820900, data source: UN Comtrade, reported by China)*

4.3. Overcapacity in China's raw tungsten production

Several significant uncertainties exist in both the supply and demand of critical materials (Erdmann and Graedel, 2011; Glöser et al., 2015; Graedel and Reck, 2016; Helbig et al., 2016). Material criticality and its impact on stakeholders from the demand side, such as product manufacturers and consumers, have been widely noticed (Bastein and Rieveld, 2015; Graedel et al., 2012; NSTC, 2018). However, the impacts on the upstream producers have rarely been explored. Based on our dynamic material flow analysis and market investigation, it is found that the international tungsten price volatility can also bring severe challenges to China's tungsten industry. According to Results 3.3, it is clearly stated that China's tungsten production increased significantly from 1980 to 2000, and as a result, China has become the world's leading producer. The low price and large quantities of China's tungsten exports lead to a rapid decline in international tungsten prices (Fig. 7(c)). However, due to the time lag (i.e., 5-20 years; (Ali et al., 2017; Graedel, 2018)) of mining and refinery projects to market supply, China's tungsten concentrate production has continuously increased despite the sustained decline in tungsten prices since 2014 (even below the mining cost price). Thus, there occurs the overcapacity issues (i.e., over 50% of current capacity remain unused (CITIC, 2018)) from China's tungsten industry, especially in the production capacity of APT, tungsten powder, and cemented carbide.

4.4. The resource endowment actually discouraged tungsten recycling in China

Tungsten is an element with a high potential for recycling. According to a recent study (Ciacci et al., 2015), about 91% of the tungsten in final products can be recycled. Nevertheless, compared with developed countries, the total recycling rate of EoL tungsten products in China is extremely low (i.e., around 10%, which is even lower than the global average, 30% according to (Zeiler, 2018)). There is a lack of recycling incentives in China due to the following reasons: (a) Metal price is critical to determine the incentive in waste collection and processing. At present, the relatively low price in tungsten is limiting the recycling and secondary production incentives in China. (b) Metal quality plays a crucial role in the feasibility of recycling. In many cases, tungsten is used with other metals in complex tools with low metal concentration forms, which can bring the technical difficulty and high-cost for tungsten recycling (Shedd, 2011; Zeiler, 2018). Besides, China has not established an effective recycling system in tungsten and other critical materials yet. Given that tungsten is becoming scarcer with the forthcoming available recyclable resource, China should urgently establish an effective recycling system for tungsten to ensure the sustainable development of the tungsten industry.

5. Conclusions

With a dynamic material cycle analysis, this study offers an in-depth and comprehensive accounting and analysis of tungsten stocks and flows in China from 1949 to 2017. Accordingly, this study can help improve our understanding of the criticality of tungsten, especially on China's role in the global tungsten supply chain. The framework and information presented in this paper can form the basis for future work related to material flow analysis for the global tungsten cycle. Key conclusions are summarized as follows:

First, although China currently has the largest amount of tungsten reserves and the largest tungsten raw material production, it still relies on the import of high-end tungsten products from other nations, which are produced from raw tungsten originally imported from China. Such interdependence among countries has been widely neglected in present material criticality studies and policies, which highlights the need for a more detailed material flow trade network analysis to deepen the understanding of material criticality.

Second, this paper indicates an urgent need for China to make sustainable resource policies on tungsten based on the dynamic and material cycle views. From the supply side, given that domestic mineral resource is becoming scarcer with declining quality, there is an urgent need for Chinese producers to improve the mineral yield rate in tungsten extraction and refinery. Besides, more innovation in the metallurgical operation is encouraged to adapt such changes. Meanwhile, this trend will also affect the long-term viability or sustainability of Chinese upstream dominance in tungsten supply, as China may seek oversea minerals with higher quality. From the demand side, strategies such as supply chain optimization, yield efficiency improvement, and technology development in the tungsten industry could help deal with its overcapacity issues. Furthermore, policies should guide stakeholders to build an effective recycling system and increase the investment of technological innovation for lowering the processing losses.

Finally, as for the research of critical materials, it is necessary to enhance the criticality framework from the whole life cycle perspective. Indeed, various factors in the whole supply chain may influence the criticality of minerals. A material flow analysis by quantifying the material's stocks and flows in the whole life cycle can provide a holistic overview of the criticality of metals and help to urge more direct strategies for supply risk mitigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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