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Mapping the global flow of tungsten to identify key material efficiency and supply security opportunities

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ABSTRACT

Tungsten is an economically important metal with diverse applications ranging from wear resistant cutting tools to its use in specialized steels and alloys. Concerns about its supply security have been raised by various studies in literature, mostly due to trade disputes arising from supply concentration and exports restrictions in China and its lack of viable substitutes. Although tungsten material flows have been analysed for specific regions, a global mass flow analysis of tungsten is still missing in literature and its global supply chain remains opaque for industry outsiders. The objective of this paper is to create a map of global tungsten flows to highlight and discuss key material efficiency (i.e., using less of a material to make a product or supply a service, or reducing the material entering production but ending up in waste) and supply security opportunities along tungsten's supply chain that could be incorporated into the planning and prioritization of future supply security strategies. The results indicate the existence of various intervention alternatives that could help to broaden the supply base and improve the overall material efficiency of the system. In particular, future policy and research and development (R&D) efforts to improve tungsten's material efficiency should focus on minimizing tungsten losses as fine particles during beneficiation and extraction (current global losses estimated at 10–40%), as well as on evaluating alternatives to improve recycling collection systems and technologies, which could lead to 17–45% more tungsten discards being recycled into new products.

1. Introduction and background

The high rate of technological evolution experienced in the world during the last three decades has resulted in the development of increasingly complex products that employ intricate material mixes. Combined with population and economic growth across the world, this has generated a rapid growth in demand for many mineral commodities that were previously not produced in large amounts. For example, 713 million smartphones were shipped globally in 2012, an increase of 44.1% over 2011 (IDC, 2013). This situation has raised concerns from governments, industries and academics about whether the non-fuel mineral resources needed to satisfy the growing economic demand will become scarce or difficult to obtain in the future. One such material is tungsten, as evidenced by its inclusion in the European Union's (EU) raw material supply criticality list (European Commission, 2014), which was motivated by its high economic importance stemming from its wide range of applications, its lack of viable substitutes, the EU's dependence on imports and trade concerns arising from China's dominant market position. Similarly, the British Geological Survey's (BGS) risk list (BGS, 2012a) ranked tungsten as number two in a supply criticality index list containing forty one elements, mainly due to alleged political instability in supplying regions and its limited number of substitutes.

Tungsten's unique properties include the highest melting point, the lowest coefficient of thermal expansion and the lowest vapour pressure of any non-alloyed metal (BGS, 2011; Lassner & Schubert, 1999). In addition, tungsten is among the heaviest metals with a density similar to that of gold and presents a high modulus of compression, high wear resistance, high tensile strength and high thermal and electrical conductivity (International Tungsten Industry Association (ITIA, 2009; BGS, 2011)). These properties make it extremely important for a large variety of products. In particular, tungsten's use in cemented carbide represents its most important application (ITIA, 2012b). Tungsten carbide is widely employed in the mining, petroleum, construction and metal-working industries in drill bits and in machine tools for shaping metals, wood, composites, plastics and ceramics (e.g. punches, stamping dies, bushes,

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rollers, milling inserts and tile and glass cutters among others) (BGS, 2011). In addition, tungsten is commonly alloyed with steel, especially in high speed steels (HSS) that allow high productivity levels in metal cutting and in superalloys with applications in the aerospace, industrial gas turbine and marine turbine industries due to high resistance to corrosion and wear (Lassner & Schubert, 1999). Other tungsten alloys find important applications in electronics, power engineering and medical devices. Pure tungsten mill products are used as light bulb filaments, vacuum tubes and heating elements. Additional applications include an extensive range of chemical uses including catalysts, colouring agents for porcelain and paint pigments, among many others (BGS, 2011).

Numerous security of supply strategies are discussed in literature (as exemplified by the summary presented in Table S1 of the supplementary information); some of the most common being mineral resource exploration incentives for supply diversification, material substitution, recycling systems and technological improvement, material re-use and waste reduction. However, the authors believe that the potential development and application of such approaches is usually hindered by the lack of transparency and data availability that exists across the supply chain of these materials, which limits the analysis of each strategy's potential material benefits and overall economic and technical feasibility. This is also a difficulty for tungsten, as evidenced by a recent study of data needs for mass flow analysis (MFA) relating to 21 raw materials (RPA, 2012), which identified tungsten amongst the five elements that have the least data available. This type of analysis (also referred to as material flow analysis or substance flow analysis) is an analytical method of mapping quantitative data about material flows and their relationships and transformations through the entire production system. Such analyses have been performed at a global level for base metals such as steel and aluminium (Cullen and Allwood, 2013; Cullen et al., 2012), as well as for materials such as rare earths (Du and Graedel, 2011a; Du and Graedel, 2011b), cobalt (Harper et al., 2012), indium (Yoshimura et al., 2011) and a joint-study for neodymium, cobalt and platinum (Nansai et al., 2014). Although tungsten flows have been analysed for the United States of America (Harper and Graedel, 2008; Harper, 2008), a global mass flow analysis of tungsten is still missing in literature and its global supply chain remains opaque for industry outsiders.

The objective of this paper is to create a global mass flow analysis of tungsten to discuss key supply security opportunities where intervention could be most effective in broadening the supply base and improving the material efficiency of the system. Such a map could work as reference material for the planning and prioritization of future supply security strategies for tungsten based on criteria such as prospective material gains, investment requirements and economic certainty/motivation, existing technological readiness, geological knowledge and understanding of potential new deposits, research and development capacity and sustainability performance. This study is also expected to contribute to tungsten's supply chain transparency by gathering the scarce public information that exists on this material and complementing it with new unpublished insights obtained by the authors through a stakeholder consultation process. The assumptions that underlie this analysis are discussed further in the next section.

2. Methodology and data considerations

This section describes the tool employed to carry out the global mass flow analysis of tungsten (Section 2.1) and the methods, assumptions and data sources used to build such analysis, including a short account of data availability issues (Section 2.2).

2.1. Description of the global tungsten Sankey diagram

The Sankey diagram has been adopted as the visualisation tool employed to present the mass flows of tungsten in this paper. Sankey diagrams applied to mass flows help to highlight inefficiencies and potential savings in connection with material use by illustrating quantitative information about flows, their relationships and their transformations, as suggested by Schmidt (2008). Since their development over 100 years ago, Sankey diagrams have been used to represent the energy and material balances of complex systems and have been widely used in industrial ecology to depict industrial metabolisms (Schmidt, 2008).

The mass flow analysis presented in this paper displays the allocation of tungsten across its supply chain by following the mining–manufacturing–use route, in addition to recycling and re-use flows and the points where material losses occur. The Sankey diagram shows the total amount of materials that were extracted, processed and used in 2010, but does not indicate the accumulated natural and anthropogenic material stocks available for human exploitation. The thickness of the flows are proportional to the amount of mass in each of them (i.e., the thickness of each link represents the magnitude of flux) and the mass balance is maintained along the diagram. Therefore, all tungsten entering and leaving the system is accounted for and any mass balance irregularities due to losses or inefficiencies are intuitively displayed (Schmidt, 2008).

Tungsten rarely exists in a pure state along the system, therefore, vertical divisions (slices) along the flows indicate where important transformative processes occur. They are accompanied by an indication of the resulting material forms and the amount of energy (including both electricity and fuel converted to kWh units) that is consumed during each transformation per unit mass, to provide an insight into their environmental cost. Additional resources and emissions involved during these material transformation processes (e.g. water, chemicals or gas emissions) have not been included due to lack of suitable data. Color is used to distinguish the different tungsten grades contained in each flow (i.e., to describe the typical tungsten concentration within the carrier materials in each flow).

2.2. Data availability and sources

The tungsten Sankey diagram presented in this paper was populated using data from a variety of industrial and academic sources. In some cases the data had to be inferred, estimated or back-calculated if the direct values were not available. In order to overcome the problem of public data scarcity, a stakeholder consultation was performed through the organisation of a workshop named "Understanding the tungsten lifecycle in Europe" (BGS, 2012b). This workshop gathered experts from across all levels of the supply chain, from mining to final manufacturing, in addition to academia and consultancies. The lead author also visited the Mittersill tungsten mine in Austria, operated by Wolfram Bergbau und Hütten (WBH, 2013), where tungsten mining experts were consulted.

Table S2 in the Supplementary Information provides additional detailed information about the methods, data and assumptions applied to the mass flow analysis to support the explanations presented in this section and to help the reader to see overall characteristics of the estimation at a glance. The mass flow estimations can be divided into five categories, as follows:

i **Mining and extraction**

a. Global mine production figures (given in metric tonnes of tungsten content), following ore beneficiation, are the starting point for the mass flow analysis building process. Global mine production data per country (67 kt for China, 9.9 kt for the rest of