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.

KEYWORDS: tungsten, mass flow analysis, material efficiency, mineral supply security.

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, 2011b). 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, 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. Colour 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 the world), flows to stock (5.9 kt) and data on total scrap input for 2010 (24 kt) were obtained from the International Tungsten Industry Association's (ITIA) website (ITIA, 2011a; ITIA, 2011b).

b. The beneficiation recovery rate for the Mittersill tungsten mine in Austria has been estimated at 75–85% (WBH, 2013), whereas that of the Los Santos project in Spain has been reported at 57–65% (Almonty, 2012) and that of the Cantung mine in Canada is around 75–79% (NATC, 2013). These numbers agree with estimates from Lassner and Schubert (1999) and Smith (1994), who have suggested that tungsten recovery rates normally range between 60–90%. A recovery rate of 75% was assumed in Figure 1. Mine production data was back-calculated considering this recovery rate to infer the amount of tungsten contained in ore prior to beneficiation. A 75% recovery rate means that out of 103 kt of tungsten mined as ore, 26 kt are lost during beneficiation, while the rest becomes the official mine production figure.

ii. Recycling routes

a. Based on data from ITIA (2011b), a total of 24 kt of tungsten were incorporated into the supply chain through the recycling of scrap from end-of-life products in 2010. As shown in Figure 1, two major recycling processes exist: the zinc process and chemical recycling. Records showing the exact amounts of tungsten scrap that were processed through each of these two methods could not be found in literature nor in industrial reports. Similarly, none of the experts consulted during the stakeholder meeting (BGS, 2012b) were able to provide information to clarify this point. Given that industrial recycling of tungsten carbide is a well-established procedure (BGS, 2012b; WBH, 2013; Weiss, 1985) and that carbide products account for at least 50% of end-products (BGS, 2011), it has been assumed that 50% of tungsten is recycled through the zinc process (12 kt), which is the preferred carbide recycling route due to its lower energy consumption and lower cost compared to chemical recycling (WBH, 2013; Weiss, 1985). The remaining 12 kt of tungsten are assumed to be recycled through the chemical route and transformed into ammonium paratungstate (APT).

iii. Fabrication of intermediate products and finished sectors

The construction of this section of the Sankey diagram involved three main steps: defining the structure and connections between its flow routes (part ‘a’), identifying relevant data and assumptions regarding the likely values for each flow (part ‘b’) and connecting these two pieces of information to back-calculate and estimate the final mass flows shown in this intermediate section of the Sankey diagram (part ‘c’).

a. The flow structure and links depicted in the intermediate section (“Fabrication of intermediate products”) have been based on previous work by Smith (1994) and a subsequent adaptation of the same work by Harper and Graedel (2008), who mapped tungsten flows for the United States. Based on this, a fraction of tungsten concentrate flows directly towards the tungsten carbide production step, while another concentrate fraction is used directly in the manufacturing of steel and alloys. A larger portion of tungsten concentrate is chemically converted to APT, which is mainly an intermediate compound used in the production of tungsten chemicals and tungsten metal powder. The latter is commonly employed to manufacture tungsten forms, ferrotungsten and tungsten carbides.
b. Mass allocation for the “Fabrication of intermediate products” section was based on the following evidence:

i. The global distribution of finished sectors was obtained from BGS (2011) (i.e. the percentage of tungsten used to produce chemicals [6%], mill products [13%], steels and alloys [27%] and carbide products [54%]). In addition, the detailed distribution of carbide products was obtained from ITIA (2010) (i.e. metal cutting [22%], wear applications [17%], stoneworking [26%], wood and plastic working [26%] and chipless forming [9%]). Moreover, information on chemical product categories was extracted from ITIA (2011c).

ii. Information about processing losses during each manufacturing step was initially obtained from the work of Smith (1994) and Weiss (1985) and later on corroborated through conversations with industry representatives (BGS, 2012b; WBH, 2013): 4% losses during APT production (2.6 kt), 1% losses during metal powder manufacturing (0.6 kt), 1% losses from transforming metal powder into tungsten carbide plus 4% losses from converting tungsten concentrate into carbide (0.5 kt in total), 4% losses during the production of tungsten chemicals (0.2 kt) and 4–5% losses from the use of tungsten concentrate in steels and alloys (0.8 kt). All these numbers combined produced an overall 5% mass loss, equivalent to 4.7 kt.

iii. Two key assumptions have been made, based on the work from Lassner and Schubert (1999): roughly 70–80% of tungsten is used in powder metallurgy and approximately 70–80% of tungsten powder is used to produce tungsten carbides. For the purpose of the Sankey diagram, these numbers were fixed at 73% and 70% respectively to ensure the system mass balance. These assumptions resulted in a total of 65 kt of tungsten (out of 88.9 kt) converted to APT and 47.9 kt of tungsten metal powder (out of 68.7 kt) allocated to carbide production.

c. Connecting the information given in part ‘b’ above while following the structure described in part ‘a’ allowed the back-calculation and estimation of all the flows that form the “Fabrication of intermediate products” section:

   i. Considering a total consumption of 95 kt of tungsten in 2010 (76.9 kt virgin tungsten + 24 kt scrap input – 5.9 kt flow to stocks) and 5% overall losses during manufacturing (4.7 kt), it was possible to allocate the appropriate shares to each finished sector (90.3 kt distributed across four categories). In this way, tungsten chemicals flowing from APT production were back-calculated to 5.6 kt (accounting for losses), tungsten forms reaching mill products were estimated at 11.7 kt, tungsten carbide going to carbide products was 48.7 kt and a total of 24.4 kt of tungsten went to steel and alloys production coming from three different sources: tungsten concentrate, ferrotungsten and tungsten forms.

   ii. After considering all the data and assumptions explained until this point, four mass flows remain undefined: the exact amount of tungsten concentrate flowing to carbide production and steel and alloys production, as well as the amount of ferrotungsten and tungsten forms flowing to steel and alloys production. The values shown for these flows in Figure 1 have been allocated by considering the expert opinions from consulted stakeholders (BGS, 2012b; WBH, 2013) and applying the conservation of mass principle. In this way, it was assumed that roughly 70% of the input for steels and alloys production came directly from tungsten concentrate (16.7 kt), while the amount of ferrotungsten used in steels and alloys manufacturing was defined as nearly double than that of tungsten forms (5.8 and 2.7 kt respectively). By mass conservation, the remaining tungsten concentrate (1.3 kt) was allocated to the production of tungsten carbide.

iv. Tungsten grades

a. The purity of each flow specified in Figure 1 has been obtained from Lassner (1995) for ore deposits, ore concentrate and tungsten scrap grades; GTP (2015) for APT; THPP (2014) for tungsten metal powder; USGS (2011) for carbide metal powder and carbide products grades; ITIA (2011d) for ferrotungsten grade; ITIA (2011e) for high speed steels, tool steels, cast steels and heavy metal alloys; Haynes (2013) for superalloys and ITIA (2011f) for heavy metal alloys.

v. Processing energy consumption

a. The energy consumption of distinct processing steps has been obtained from USDOE (2007) and consultation with industry specialists (WBH, 2013) for mining, extraction, handling and beneficiation; Krishna Rao (1996) for general beneficiation figures; De Wang et al. (1995) for APT production from concentrate; Hairunnisha et al. (2007) for APT production from scrap; Acharyulu and Rama Rao (1996) and Suchkov et al. (1971) for tungsten powder production from concentrate; and Acharyulu and Rama Rao (1996) and Gürmen and Friedrich (2004) for powder production from tungsten carbide scrap. Additional information on energy estimates is presented in Table 2. Data availability on tungsten's mining and processing energy intensities is low and therefore the data presented in Table 2 does not necessarily represent all existing technologies or best practices across the industry, but simply shows the data that is available in literature.

3. Results

Figure 1 presents the global mass flow of tungsten through its entire supply chain in 2010, as well as the energy requirements of key transformation processes and the material grades of main flows. The total mine production of tungsten in 2010 was 76.9 kt (ITIA, 2011a), in addition to the consumption of around 24 kt of scrap from end-of-life products (ITIA, 2011b). The tungsten lifecycle starts with the mining of tungsten ore minerals, chiefly scheelite and wolframite, which contain about 80.6% and 76.5% tungsten trioxide (WO_3) respectively (BGS, 2011). The ore grade of tungsten deposits varies between 0.08–1.5% of WO_3 (i.e. 0.06-1.2% tungsten metal content), as indicated in Figure 1. Mining is an energy intensive activity, requiring 20.3 kWh per metric tonne of processed ore (including both electricity and fuel converted to kWh units). The tungsten-containing minerals are extracted from ore through traditional beneficiation techniques such as crushing, grinding, magnetic, gravity and flotation separation, to form market-grade concentrates with WO_3 contents between 15–75% WO_3 (i.e. 12–60% tungsten metal content) (BGS, 2011). The beneficiation process is slightly less energy intensive than mining, requiring 13–15 kWh per tonne of processed ore.

The resulting tungsten concentrate can either be used directly as an alloying element in steel or converted to intermediate tungsten compounds through hydrometallurgy (mostly to APT with a typical WO_3 content of 89.5%, or 71.6% tungsten content (GTP, 2015)). This process requires 1,600 kWh per tonne of APT produced. Intermediate compounds can be further refined through pyrometallurgy, leading to the production of tungsten metal powder containing >99% tungsten (THPP, 2014) and typically requiring 12,000–20,000 kWh per tonne of powder produced. Tungsten metal powder is then converted into final products, mostly in the form of tungsten carbide for cutting tools (65–95% tungsten content) (USGS, 2011), ferrotungsten (75–85% tungsten content) (ITIA, 2011d) for steels and alloys (with final tungsten contents ranging between 0.03 and more than 90% (ITIA, 2011e; ITIA, 2011f; Haynes, 2013)) and tungsten metal for mill products such as wires, rods and sheets containing more than 99% tungsten (BGS, 2011). An additional application is the production of chemicals with low tungsten content such as tungsten oxides, tungstates, tungstic acid and tungsten sulphides.

Secondary supply of end-of-life scrap is also incorporated into the supply chain presented in Figure 1, mainly through chemical recycling (hydrometallurgy) and the zinc process, which result in the production of APT and tungsten metal powder, respectively. Figure 1 indicates that the zinc process has a higher energy consumption of around 4,000–6,000 kWh per tonne of tungsten processed, compared to 2,000 kWh per tonne for chemical processing. Both represent viable recycling routes for this material.

The supply chain presented in Figure 1 has an overall mass efficiency (measured as the ratio of output of tungsten mass to input of tungsten mass) of about 71% (which varies between 55% and 83% for worst- and best-case scenarios based on the beneficiation and intermediate processing losses shown in Figure 1). Key aspects of the global tungsten map are discussed in the following section.

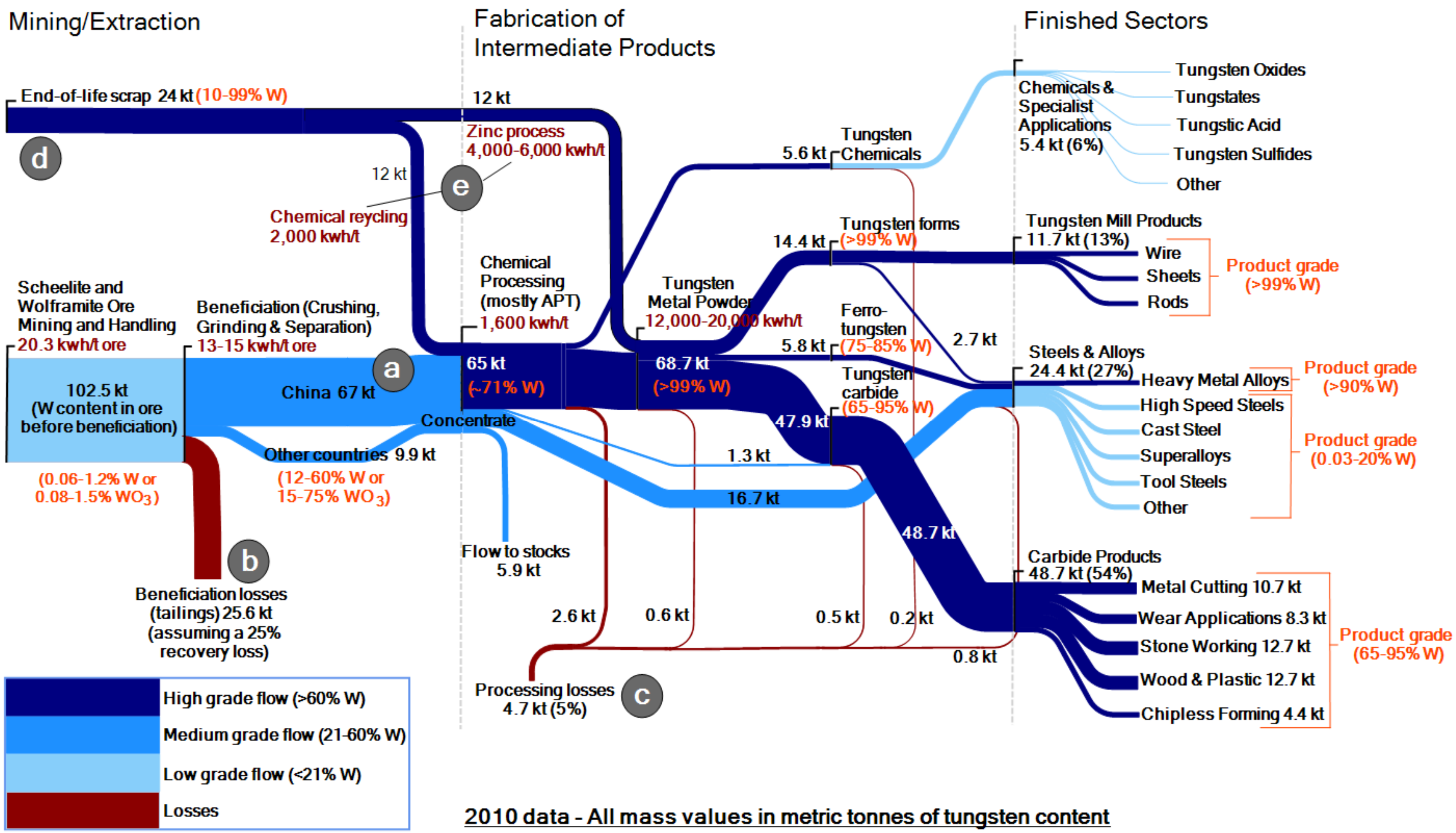

Figure 1: Global mass flows of tungsten in 2010. The grade of different flows and the energy consumption of selected processes are indicated with orange and red text respectively. Note: the letters are referred to in section 4

4. Discussion

The following key messages have been highlighted in Figure 1 (each item in the list indicated in Figure 1 under the same letter):

a) In 2010, China accounted for about 87% of all mine production.
b) Tungsten's beneficiation process leads to considerable losses (10–40% of the tungsten content of the ore may be lost).
c) Processing losses during the fabrication of intermediate products are comparatively lower (<5%). In addition, nearly three quarters of all tungsten are processed through powder metallurgy and about half of total tungsten is used to manufacture carbide products.
d) Roughly 25% of total tungsten supply came from end-of-life scrap in 2010.
e) Based on their processing energies, tungsten recycling is less energy intensive than virgin production. Figure 1 presents the latter in terms of energy per tonne of processed ore given that tungsten content in ore can vary greatly. At a typical cut-off ore grade of 0.2% [WBH, 2013], virgin production results in roughly 10,000 kWh per tonne of tungsten, in comparison to <6,000 kWh per tonne of tungsten for recycling (More details in Section 5.5).

The analysis of tungsten flows shown in Figure 1 leads to important questions, as discussed in Sections 4.1-4.5.

4.1 Can we develop alternative supply chains in the rest of the world?

Historical evidence suggests that China has not always been the dominant actor in the tungsten market. Figure 2 (Brown, 2012) shows that although global tungsten mine production barely changed between 1980 and 1990, totalling little more than 50 kt, China's share of the total changed from only 29% in 1980 to 62% in 1990, increasing even further in the following years.

As shown in Figure 3, tungsten prices rose significantly in the early 1970s, reaching US$164 per metric tonne in 1977 (USGS, 2013). Brown (2012) and the USGS (2013) suggest that a supply shortfall in 1978 had to be compensated by the release of US Government stockpiles and increased exports from China, with prices falling as a result. Reduced demand from Western Europe caused by the 1981 global recession, coupled with an increase in the supply of Chinese tungsten concentrates and intermediate products at cheaper prices than those from Western sources, contributed to a downward trend of tungsten prices until the mid-1980s, reaching a low point in 1986 (Brown, 2012; USGS, 2013) (Figure 3). Despite strong demand between 1986 and 1990, prices continued to be relatively low as a result of continuous oversupply from China at cheaper prices (USGS, 2013). This trend was exacerbated in the early 1990s, when the oversupply from China coincided with a period of reduced demand due to another global recession and a reduction in imports to the former Soviet countries following the 1991 breakup of the Soviet Union (Brown, 2012; USGS, 2013). Low prices during such an extended period of time led to the closure of a significant number of mines in the Western world, leaving China as the main player in the market. Once demand and prices started to recover, Chinese producers were able to react more quickly and, as a consequence, China's output grew rapidly compared to other nations (Brown, 2012).

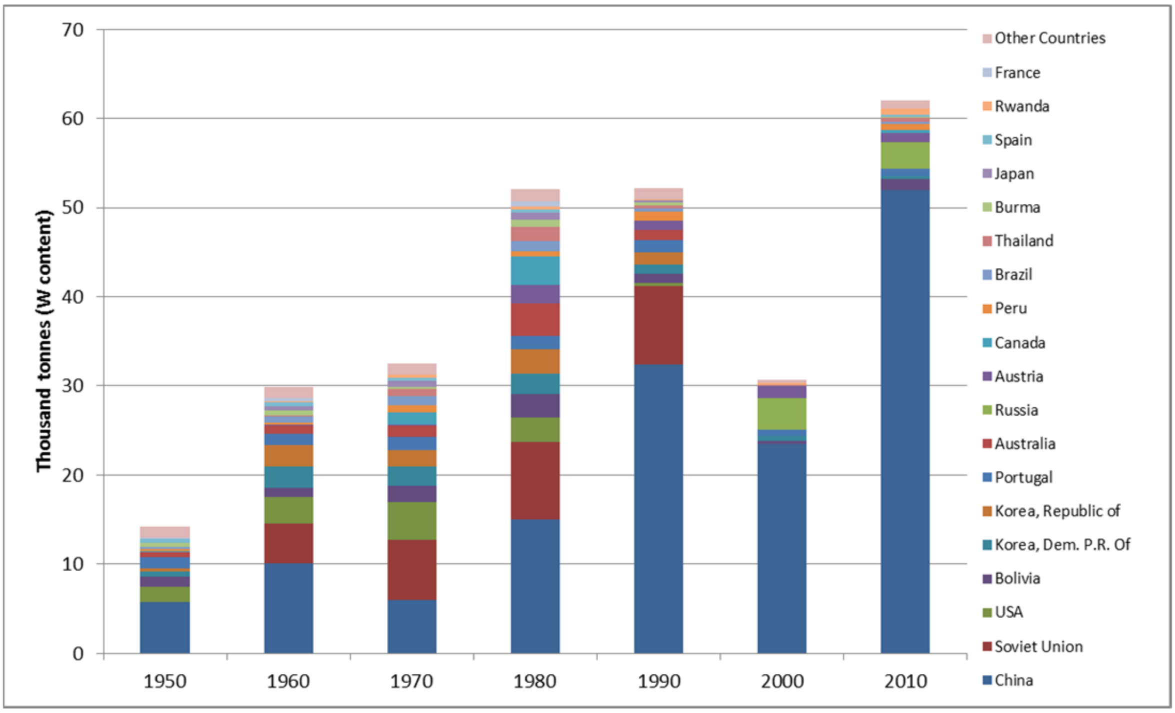

Figure 2: Evolution of tungsten production concentration 1950–2010 (Data from Brown (2012)).

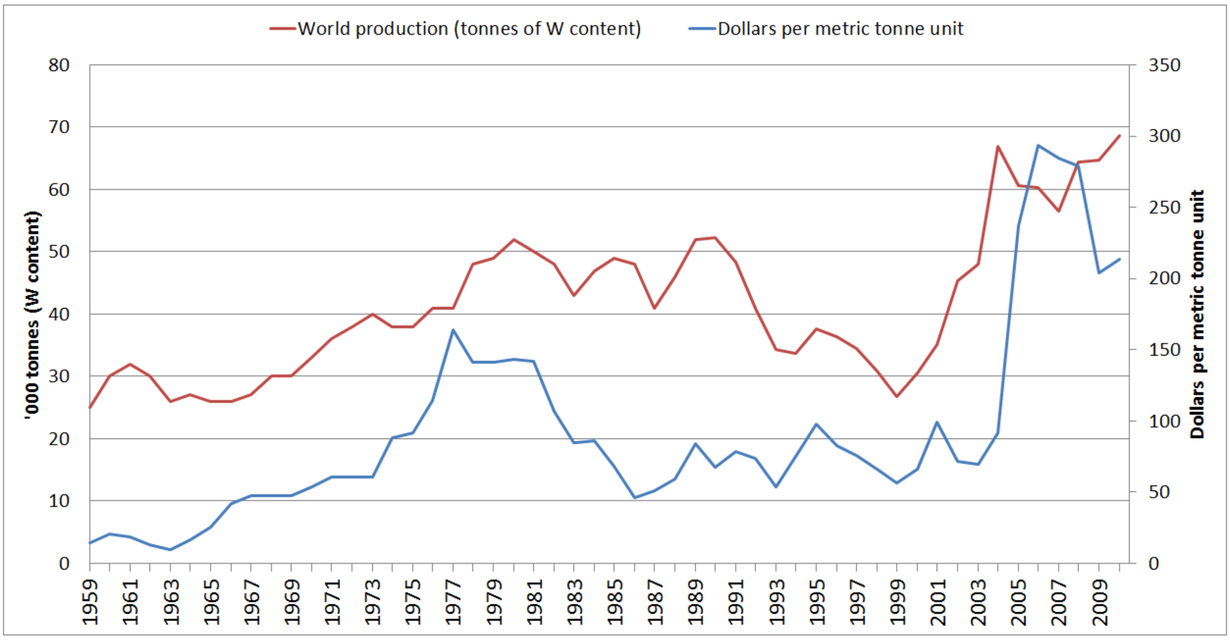

Figure 3: Historical tungsten production and unit value 1905–2010. Production data in tonnes of W content (Data from BGS (2013)). Prices in dollars per metric tonne unit (Data from USGS (2013), converted from short ton to metric tonne).

Several tungsten mining projects are under development worldwide, both for newly discovered deposits and for the reopening of dormant mines (Table 1), indicating that supply diversification is possible. These may contribute to global supply in the near future, given favourable market conditions, and help to reduce China's dominant position as a result.

Name	**Country**	**Current Status** (as at Feb 2015)	**Possible Production**	**Resources (tonnes contained tungsten)**
Hemerdon	United Kingdom	Feasibility study completed May 2011, mine construction started early 2014	2015	>420,000
Mount Carbine	Australia	Tailings retreatment commenced in 2012, reopening of hard rock mine scheduled for 2016	2016	>50,000
Watershed	Australia	Feasibility study completed Sept 2014, permitting completed Dec 2013, raising funds	2016 or 2017	>55,000
Barruecopardo	Spain	Feasibility study completed Feb 2012, mine permit granted Nov 2014, raising funds	2016 or 2017	>55,000
King Island	Australia	Feasibility study completed Feb 2012, all permits in place, updated resources and reserves statement Sept 2014, progressing with raising funds	2016 or 2017	>195,000
Sisson Brook	Canada	Feasibility study completed early 2013, permitting expected in 2015, raising funds	2017?	>270,000
Sangdong	South Korea	Feasibility study completed April 2012, updated January 2015	unknown	>280,000
Mactung	Canada	Feasibility study completed 2009, environmental permitting completed in 2014	Unknown	>370,000
Northern Dancer	Canada	Preliminary economic assessment completed in 2011, development currently suspended	Unknown	>390,000
O'Callaghans	Australia	Prefeasibility work continuing	Unknown	>200,000

Table 1: Selected major developing tungsten deposits and those where production is expected in the near future. Note: Resources are from all categories and in some cases include reserves (Data compiled from individual company reports and websites).

Known tungsten deposits occur in many countries of the world, as illustrated by Brown & Pitfield (2014). Detailed, up-to-date figures for global resources of tungsten are difficult to obtain but Hinde

(2008) estimated the total to be approximately 7 million tonnes of contained tungsten. In addition to the locations mentioned in Table 1, significant deposits are known to exist in Kazakhstan, Russia and the United States as well as China (Brown & Pitfield, 2014). The United States Geological Survey estimates worldwide reserves of tungsten to be approximately 3.3 million tonnes, with 42% of those reserves being located outside of China (Shedd, 2015).

The evidence described in this section suggests that it is possible to develop alternative supply chains; however these are subject to financing being available to open projects outside China, which depends on the perceptions of investors with regards to risks. Detailed discussions of the many factors that affect supply diversification are beyond the scope of this paper. Reducing the dominance of China in the supply of tungsten will require both time and appropriate policy efforts.

4.2 What variables determine beneficiation losses and how can they be reduced?

Beneficiation losses are mostly attributed to the friable nature of tungsten minerals (WBH, 2013; Weiss, 1985), which leads to the excessive generation of fine particles (<25 μm) during ore grinding and crushing to liberate tungsten minerals from the rest of the gangue material. As suggested by Wills (1988), a mineral deposit will be economic to work if its contained value per tonne is higher than the sum of total processing costs (including mining and subsequent separation steps) plus losses and other costs per tonne. In other words:

$$\text{Contained value} / t > (\text{total processing cost} + \text{losses} + \text{other costs}) / t$$

In the case of tungsten, mining represents a major cost. This is because the mining methods required to exploit underground vein-type deposits such as tungsten deposits are among the most expensive, as suggested by Wills (1988). Therefore, a balance is required between beneficiation costs and material losses if the economic viability of the entire operation is to be preserved. This means that sometimes losses have to be tolerated in exchange for less efficient but more cost-effective processing methods. Even if more efficient beneficiation methods exists, these need to be economical enough to guarantee that total costs do not exceed the contained value of the deposit. There are two traditional approaches for solving this trade-off between cost and efficiency: either by creating economic methods to avoid the creation of tungsten fines in the first place or by developing economic processes for extracting these tungsten particles from waste slimes and tailings.

Fine tungsten particles are hard to capture by the most widely used separation methods and are commonly lost in slimes and tailings instead, from where it is even harder to recover the tungsten (Weiss, 1985; WBH, 2013; Krishna Rao, 1996). Tungsten minerals are friable and tend to be ground preferentially during crushing and grinding. Also, due to their high density, tungsten particles can be misclassified by cyclones or hydraulic classifiers, often being sent to the over-size fraction and getting recycled to the grinding mill, resulting in over-grinding (Krishna Rao, 1996). This argument has been supported by Clemente et al. (1993), who provide an applied example from a wolframite mine at Minas da Panasqueira in Portugal. In this mine, tungsten ore is crushed to a coarse average size of 2.25 mm to liberate the tungsten minerals from the gangue. The higher friability of wolframite compared to the rest of the gangue minerals in the ore means that wolframite tends to end up disseminated in fine particle form, leading to a fines feed with almost double the tungsten content than the rest of the plant feeds. Most of these fine wolframite particles (below 25 μm) end up in tailings, where they are mixed with a wide range of other minerals, complicating their recovery through normal separation methods. The same problem has been reported with scheelite at the Mittersill tungsten mine in Austria (WBH, 2013). Scheelite losses are exacerbated when extracted from low grade ores, as this type of rock requires even finer grinding to liberate scheelite from gangue material, leading to higher losses of tungsten as fine particles in slimes (Marinakis and Kelsall, 1987).

Multi-stage crushing and grinding has been suggested by Krishna Rao (1996) as an effective technique to reduce the excessive generation of tungsten fine particles. In this process, multi-stage sizing of the ore takes place, attempting to recover as much tungsten as possible from each size at each stage. Selective disintegration has also been suggested by Chanturiya (2008) who advocates substituting the traditional processes of crushing and grinding in jaw and cone crushers and ball mills by processes that cause disintegration across the boundaries of mineral grains and thus promote mineral liberation with reduced fines production. Other approaches to avoid losses by over-grinding include coarse narrow-range grinding of wolframite by rod milling, as proposed by Jakhu and Ray (1996) who have reported eighty per cent liberation of wolframite by this process.

The extraction of tungsten fine particles from tailings has been investigated by Clemente et al. (1993), who mention high-efficiency slimes gravity separators and new flotation reagents as examples of processing technologies capable of extracting tungsten from slimes. A three-stage gravity separation process developed and tested by Clemente et al. (1993) was capable of producing a 50–55% WO_3 concentrate from tungsten slimes at Minas da Panasqueira in Portugal, achieving a 68–73% recovery of tungsten particles in the 10–125 μm range and about 50 to 54% of all tungsten contained in the tailings of that mine. In summary, it is technically feasible to minimise the dissipation of tungsten during beneficiation by reducing the production of fine tungsten particles through optimisation of the comminution stages and/or recovering tungsten from tailings when economic conditions allow it. However, the technical viability of these approaches has to be accompanied with economic viability for these methods to be utilised.

4.3 What factors explain the high material efficiency observed during fabrication?

Tungsten’s high economic value tends to ensure its efficient use during manufacturing of intermediate and consumer products (WBH, 2013). As a result, intermediate processing losses are significantly lower than beneficiation losses, ranging from 1 to 4% (BGS, 2012b; WBH, 2013; Smith 1994; Weiss, 1985), as shown in Figure 1. Although there is no available data on the generation and recycling of internal scrap during the manufacturing of intermediate and consumer products, Smith (1994) and WBH (2013) have suggested that there is a high and efficient reuse of this type of scrap in manufacturing facilities (closed-loop recycling). In addition, between 70 and 80% of tungsten products are manufactured through powder metallurgy (Lassner and Schubert, 1999), which is a highly efficient and controlled technique in which losses are minimised and waste material is efficiently recovered and reused.

4.4 What are the main barriers towards achieving higher recycling rates?

Tungsten recycling is not significantly constrained by technological availability, but rather by its use in some applications where recycling is not possible due to dispersion or dilution and by the lack of appropriate post-consumer collection systems.

Acharyulu and Rama Rao (1996) indicate that tungsten scrap is commonly available in four main forms: pure tungsten metal scrap, heavy alloy scrap, tungsten carbide scrap and tungsten-containing steels. Available tungsten recycling processes and the type of scrap they can process are discussed in the work of Acharyulu and Rama Rao (1996), while schematic views of these recycling methods can be seen in a report from Smith (1994). High-grade scrap such as cemented carbides, which account for the largest fraction of scrap resources, can be recycled by direct physical re-use methods or by semi-direct and indirect chemical processing (Reuter et al., 2013). The two most common direct re-use methods include the zinc and coldstream processes, with the former being preferred over any other method due to its high efficiency (>95%), lower cost and higher energy efficiency (Acharyulu and Rama Rao, 1996). Heavy alloy scrap (over 90% tungsten content) and tungsten mill products (considered as pure tungsten metal scrap) are valuable raw materials due to their high tungsten fraction. These materials can be recycled through chemical digestion, coldstream/crush, oxidation/reduction and chemical separation routes.

In contrast, tungsten contained in ferrous and non-ferrous alloys with low tungsten fractions (cast steels, high-speed steels, tool steels, etc.) is not commonly recycled, as most of it is diluted during the recycling of steel, as suggested by Smith (1994). In a similar way, tungsten used for chemical and specialist applications is generally not recycled due to the high dispersion of the material in these applications (BGS, 2012b; Smith, 1994).

Even more significant than dispersion and dilution, there seems to be a general consensus among industry members that the biggest limitation affecting tungsten recycling is the lack of appropriate post-consumer collection systems for open-loop recycling (WBH, 2013; BGS, 2012b). The industry's tendency towards vertical integration could help to ensure an efficient recycling of internal scrap (BGS, 2012b). However, more awareness is required among end-product consumers with respect to the potential economic advantages of implementing efficient collection systems and strategies. Practical initiatives such as take back schemes between manufacturers and end-users have already been reported (WBH, 2013). These represent a move towards the achievement of higher recycling rates. Additionally, current high prices of tungsten are already pushing end-users to pursue alternative material efficiency strategies such as re-designing the same products with less tungsten. Examples have been reported where the tungsten content of specific carbide tools has been reduced by as much as 90% through product re-design (WBH, 2013). In summary, dispersion, dilution and lack of collection infrastructure are the key factors limiting global tungsten recycling.

4.5 Are energy efficiency benefits sufficient to incentivise recycling?

The energy estimates presented in Figure 1 (a detailed breakdown of these numbers is shown in Table 2) indicate that virgin material mining and handling plus beneficiation accounts for roughly 2,700–58,800 kWh per tonne of W content. This large range is related to variation in ore grade of 0.06–1.2% W (0.08–1.5% WO_3), although cut-off grades below 0.2% are uncommon (WBH, 2013; Weiss, 1985) (the average energy consumption in Mittersill is about 10,500 kWh per tonne of W content for an ore grade of 0.3% WO_3). In comparison, recycling through the chemical route leads to a lower energy consumption of 2,000 kWh per tonne of W content. Similarly, tungsten powder production from virgin ore involves four steps: mining and handling, beneficiation, chemical processing to APT and powder production. Adding these processes leads to roughly 16,300–80,400 kWh per tonne of W content, which is a much higher figure than the 4,000–6,000 kWh per tonne of W content employed during direct scrap re-use through the zinc process.

Despite these energy savings, tungsten recycling is not necessarily cheaper than buying ore concentrate. Depending on market conditions, product fabrication through the virgin and recycled routes may have similar costs, as the cost of tungsten scrap may be even higher than that of tungsten concentrate (for example, ~US$15,000 per tonne of carbide scrap [Tungsten Carbide Recycling, 2015] versus ~US$14,000 per tonne of Chinese concentrate [MetalBulletin, 2015]). However, recycling benefits are not only measured in terms of energy and cash savings, but also in terms of material efficiency, supply security and reduced environmental impacts. Tungsten mining and beneficiation are processes with high losses (10–40%), while recycling routes have high yields (>95%) (WBH, 2013; Weiss, 1985). Although primary production can never be entirely substituted by recycling as demand grows from year to year (Tercero Espinoza, 2012), recycling could help to secure an efficient secondary supply of tungsten that requires lower processing energies, generates lower carbon emissions and avoids rock waste and leachates from mining operations. In summary, energy efficiency is not enough to incentivise recycling because the economic benefits are not sufficiently obvious. However, the positive environmental benefits associated with recycling could help to offset the negative environmental impacts related to material losses in primary production and improve supply security, hence representing an extra incentive for the organisations involved.

Processing step	**Energy (kWh/t)**	**Comments**	**Source**
Ore mining & extraction			
▪ Drilling	0.4 *	USA best practice across the whole metals sector	(USDOE, 2007)
▪ Blasting	2.2 *		(USDOE, 2007)
▪ Digging	1.5 *		(USDOE, 2007)
▪ Ventilation	1.3 *		(USDOE, 2007)
▪ Dewatering	0.2 *		(USDOE, 2007)
▪ Materials handling	14.7 *		(USDOE, 2007)
Beneficiation and processing			
▪ Crushing	0.4 *	USA best practice	(USDOE, 2007)
▪ Grinding	14.4 *	USA best practice	(USDOE, 2007)
▪ Beneficiation general	12.8 *	Wolframite ore in India	(Krishna Rao, 1996)
Ore mining & extraction plus beneficiation and processing in Mittersill mine, Austria	31.7 *	Scheelite concentrate production from ore in Mittersill, Austria	(WBH, 2013)
APT production from concentrate	1600	Solvent extraction method (99.87% efficiency)	(De Wang et al. 1995)
APT production from scrap	2000	Anodic dissolution method	(Hairunnisha et al. 2007)
Powder from concentrate	12,000-20,000	Chemical and electrolytic methods	(Acharyulu and Rama Rao, 1996 [for 12,000 kWh/t value]; Suchkov et al. 1971 [for 20,000 kWh/t value])
Powder from WC recycling	4,000-6,000	Zinc process (>95% efficiency)	(Acharyulu and Rama Rao, 1996; Gürmen and Friedrich, 2004)

Table 2: Energy estimates presented in Figure 1 (*units in kWh/t ore), including both electricity and fuel consumption converted to kWh units.

5. Conclusions

This paper has mapped the global mass flows of tungsten, from mining to end-use sectors, for the year 2010 and identified key areas where intervention would be beneficial to broaden the supply base and increase the material efficiency of the system. The evidence gathered in this analysis suggests that, although tungsten is susceptible to real risk factors and bottlenecks, there are also options for change. Future R&D work to improve tungsten's material efficiency should focus on two main priority areas. The first should investigate ways of avoiding tungsten losses as fine particles during beneficiation (both by the optimisation of comminution and recovery from tailings) and improving the economics of the process. Considering that tungsten recovery rates normally range between 60–90%, as reported by Lassner and Schubert (1999) and Smith (1994), this could potentially lead to a 10–40% recovery improvement. The second priority area should investigate how to increase awareness of tungsten's recycling value, examine what are the current limitations of recycling collection systems and recovery technologies and evaluate alternatives for improvement. Considering that the supply chain presented in Figure 1 has an overall mass efficiency varying from 55% to 83% for worst- and best-case scenarios, the potential impact of improved recycling could oscillate between 17% and 45% more recovered tungsten.

As a complement to these lines of research, it is necessary to complete a detailed analysis of finished products that contain tungsten, which is missing from this study. An analysis of such type could be extended to cover historical tungsten consumption to provide a model output of end-of-life scrap that could give a valuable estimation on the current and future size of the tungsten stock available for recycling from end-of-life products. In addition, an economic analysis (cost-benefit analysis) which identifies the factors that promote and/or hinder tungsten beneficiation optimisation and recovery is missing from this study. This should explore the cost of current practices and the cost of new technologies against market trends at global level. The economic analysis should investigate geographical differences (i.e. China vs Europe) or sector scale variance (small vs big deposits) and identify if any of the above could result in process optimisation and recovery from mine waste.

Future policy efforts to ensure a secure supply of tungsten should consider promoting two main strategies. The first should investigate and evaluate the potential benefits of providing economic incentives for investors and companies willing to explore and develop new tungsten resources and/or re-evaluate known resources outside China to reduce or eliminate dependence on Chinese exports and reduce Chinese influence over prices. This could not only include mining activities but also fabrication and manufacturing of intermediate tungsten products outside of China, where current skills and infrastructure are mainly located. The second approach should investigate the applicability of alternative material efficiency strategies at product level, including the use of less material by design and lifetime extensions for specific key products (e.g. tungsten carbide tools). As with recycling, this line of research would require a detailed analysis of finished products that contain tungsten and available manufacturing technologies to identify available efficiency opportunities.

Finally, various knowledge gaps have been identified through the development of the global mass flow analysis for tungsten, including the amount of material contained in both closed and open recycling loops, the resource intensity of different processing routes (including up to date energy consumption figures), material losses along the entire supply chain, data on the fabrication of intermediate products and mine production data discrepancies. Initiatives to fill in these data gaps in future work could include two strategies. The first is to improve stakeholder engagement by academics. Direct and extensive communication with stakeholders, as attempted in this paper through the organisation of a stakeholder workshop and a visit to a tungsten mine, is recommended as a suitable approach to obtain non-commercially sensitive data that would otherwise remain unknown. The second strategy is to increase sustainability reporting by industry. Although it might be difficult to convince companies to report their sustainability indicators without direct regulation by governments, voluntary reporting initiatives such as that promoted by the Global Reporting Initiative (GRI, 2015) have demonstrated their value to help organisations become more sustainable and improve their reputation with the wider public. In the case of tungsten, this initiative should be championed by the International Tungsten Industry Association and the International Council on Mining and Metals across different countries and supply chain stakeholders, to improve the transparency of its supply chain.

The priority areas, strategies and initiatives outlined above, especially if combined together, would result in much greater material efficiency and supply chain transparency for tungsten and may eventually lead to a reduction in the supply security concerns identified at the start of this paper.

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SUPPORTING INFORMATION

A detailed analysis of mineral supply security literature together with a breakdown of the methods, data and assumptions used to create the mass flow analysis presented in Figure 1 are contained in the supporting information.

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