SI Mapping the Global Flow of Tungsten to Identify Key Material Efficiency and Supply Security Opportunities

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Table S1: Mineral supplysecurity mitigation strategies, literature overview (selected references, modified from analysis by Fromer et al [2011], with extrasources added to the analysis).

Study	**Materials covered**	**Mitigation proposals**
Critical Material Strategy ***[USDOE, 2010]***	Li, Y, Co, Ga, In, Te, La, Ce, Pr, Nd, Sm, Eu, Tb, Dy	**General** ▪ Expand or vary number of producers across industry. ▪ Invest in material substitution R&D. ▪ Follow material efficiency strategies: recycling, reuse, and improved yields. ▪ Increase transparency and data availability across supply chain.
Critical Raw Materials for the EU ***[European Commission, 2014]***	▪ Sb, Be, Co, Ga, Ge, In, Mg, Nb, Pt, Pd, Rh, Ru, REEs, Ta, W, Fluorspar and Graphite.	**General** ▪ Periodical review of critical elements list (five year intervals). ▪ Increase transparency and data availability across supply chain. ▪ Encourage the use of life cycle analysis. ▪ Investigate future demand forecasts, including new technological advances. ▪ Incentivise resource exploration and supply diversification. ▪ Improve collection and recycling systems. ▪ Invest in material substitution R&D.
Critical metals for future sustainable technologies and their recycling potential ***[UNEP, 2009]***	▪ Pd, Pt, RE, Te, In, Ge, Ga, Ru, Li, Ta, Co	**Recycling** ▪ Enlargement of recycling capacities ▪ Development of new recycling technologies ▪ Improvement of international recycling infrastructures **General** ▪ Promote UNEP and EU research and policy on short-risk metals. ▪ Promote R&D on rare earth elements. ▪ Promote R&D on metals with serious technical recycling problems. ▪ Promote R&D on recycling technologies of specific products (e.g. solar panels & LCD monitors) ▪ Legislation measurements and evaluations (WEEE, etc.) ▪ Encourage regional (EU) and international organizations (UNEP, OECD) to improve monitoring and controlling of illegal scrap-exports containing critical metals. ▪ Promote know-how transfer and international cooperation regarding the increasing stocks of used products in developing countries
Minerals, critical minerals, and the US economy ***[USNRC, 2007]***	▪ Cu, PGMs, REs, Nb, Ga, In, Li, Mn, Ta, Ti mineral concentrates, Ti metal, V	**General** ▪ The US federal government should continue and enhance its data collection, dissemination, and analysis of minerals data and information. ▪ The US federal government should enhance its data collection and analysis ▪ The USGS Minerals Information Team should have greater authority and autonomy, as well as sufficient resources to carry out its mandate. ▪ The USGS Minerals Information Team should establish formal mechanisms for communicating with users, governmental and nongovernmental organizations or institutes, and the private sector, on the types and quality of data and information it collects, disseminates, and analyses. ▪ The USGS Minerals Information Team should be organized to have the flexibility to collect, disseminate, and analyse additional, non-basic data and information, in consultation with the users, as specific minerals and mineral products become relatively more critical over time (and vice versa). ▪ Promote R&D to encourage innovation in the critical minerals and materials area, including global mineral availability and use.

Study	Materials covered	Mitigation proposals
Critical metals in strategic energy technologies ***[ECJRC, 2011]***	▪ Te, In, Sn, Hf, Ag, Dy, Ga, Nd, Cd, Ni, Mo, V, Nb, Cu, Se, Pb, Mn, Co, Cr, W, Y, Zr, Ti	**Mitigation strategies** ▪ Supply-chain analysis ▪ Expanding primary output ▪ Promote reuse, recycling and waste reduction ▪ Promote substitution **Specific recommendations** ▪ Improve data collection and analysis on demand, supply and price trends ▪ Support and sustain the existing rare earths supply chain in Europe ▪ Fast-tracking exploration and permitting of European rare earths deposits ▪ Engage in dialogue with zinc, copper and aluminium refiners over by-product recovery ▪ Incentivise by-product recovery in zinc, copper and aluminium refining in Europe ▪ Promote R&D of recycling technologies and end-of-life collection systems ▪ Invest in alternative technologies to substitute technologies that rely on critical materials ▪ Promote R&D into indium and tin oxides substitution ▪ Encourage substitution of tellurium use in low-value applications
Materials critical to the energy industry ***[Achzet et al, 2011]***	▪ Cd, Cr, Co, Cu, Ga, Ge, In, Li, Mo, P, Pt, K, REE, Rh, Ag, Te, W, U, V	**No recommendations given**
Energy critical elements: securing materials for emerging technologies ***[APS-MRS, 2011]***	▪ La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Tb, Lu, Sc, Y, Ru, Rh, Pd, Os, Ir, Pt, Ga, Ge, Se, In, Te, Co, He, Li, Re, Ag	**General** ▪ Establishgroup of experts to supervise energy critical elements. ▪ Increase transparency and data availability across supply chain. ▪ Improve collection and recycling systems. ▪ Invest in material substitution R&D.
Material Security: Ensuring Resource Availability for the UK Economy ***[REKTN, 2008]***	▪ Au, Rh, Hg, Pt, Sr, Ag, Sb, Sn, Mg, W, Bi, Pd, Ni, B, Mo, Zn, Ho, Tb, CaF_2 , As, C, NH_3, Co, Eu, Gd, Os, Nb, Kyanite, Be, Ru, Ge, Cr, C, V, Ba, Te, Pb, Ga, In, I, Cu, Fe, Zr, Se, Lu, Br, Si, Re, $BaSO_4$, Na_2CO_3, $H_2Mg_3(SiO_3)_4$, Al_2SiO_5, $B(OR)_3$, Asbestos, Vermiculite, Diatomite, Mica, Feldspar, Bentonite, Perlite,	**General recommendations** ▪ Substitution ▪ Minimisation of material use ▪ Closing substance loops ▪ Minimisation of dispersal of residuals into the environment **Recommendations for policy makers** ▪ Incorporate social costs of environmental impact into mining and metal production ▪ Assist developing nations with environmental and social regulation of industries ▪ Encourage aggregation rather than dispersal of insecure metals to the environment ▪ Promote recycling and recovery of environmentally beneficial metals **Recommendations for business** ▪ Promotion of products mined and produced using green strategies ▪ Voluntary codes and agreements to incorporate environmental externalities ▪ Product design to discourage dispersal to the environment and easier recovery ▪ Adopt Life-Cycle management policies **Recommendations for innovation funders** ▪ Encourage projects that develop substitutes for the least secure metals ▪ Consider displacement effects of “green” technologies using insecure materials ▪ Encourage technologies that generate substitutes for insecure materials ▪ Encourage “mining” of waste streams for insecure metals ▪ Stimulate sustainable design approaches that consider overall life-cycle issues

Table S2 – Methods, data and assumptions applied to the mass flow analysis presented in Figure 1 in the main text.

Data categories	Values	Key sources and/or assumptions	References
A. Mining and extraction			
1. *Tungsten contained in ore prior to beneficiation*	102.5 kt	Estimate based on a 75% beneficiation recovery rate (see item 2 'Beneficiation losses' below) and total global mine production of 76.9 kt in 2010 (see item 3 'Global mine production by country' below). Therefore tungsten contained in ore prior to beneficiation equals: [76.9kt / 0.75 = 102.5 kt]	
2. *Beneficiation losses*	25.6 kt	A 75% beneficiation recovery rate has been assumed based on data from three tungsten mines and literature, as shown below. Therefore beneficiation losses are equal to 25% of the total mined tungsten: [102.5 kt x 0.25 = 25.6 kt]. Beneficiation recovery rates:	
		- Mittersill, Austria: 75-85%	[WBH, 2013]
		- Los Santos, Spain: 57-65%	[Almonty, 2012]
		- Cantung, Canada: 75-79%	[NATC, 2013]
		- Literature: 60-90%	[Lassner and Schubert, 1999; Smith, 1994]
		- Assumed in Figure 1: 75%	
3. *Global mine production per country*			
- China	67 kt	Data from the International Tungsten Industry Association (ITIA).	[ITIA 2011a; 2011b]
- Rest of the world	9.9 kt	Data from the International Tungsten Industry Association (ITIA).	[ITIA 2011a; 2011b]
4. *Flows to stock*	5.9 kt	Data from the International Tungsten Industry Association (ITIA).	[ITIA 2011a; 2011b]
B. Recycling routes			
5. *Total scrap input*	24 kt	Data from the International Tungsten Industry Association (ITIA).	[ITIA 2011a; 2011b]
6. *Zinc recycling*	12 kt	Exact amount of tungsten recycled by each route is unknown. ***Key assumptions:*** Industry specialists (17, 18) suggest that tungsten carbide recycling through the zinc process is a well-established procedure. Given that tungsten carbide products account for more than 50% of tungsten end-use (see item 9 below 'Finished sector distribution'), it is assumed that half of the recycled tungsten corresponds to carbide products processed through Zinc recycling. The rest is assumed to be recycled through the Chemical route.	[BGS, 2012; WBH, 2013]
7. *Chemical recycling*	12 kt		[BGS, 2012; WBH, 2013]

Data categories	Values	Key sources and/or assumptions	References
C. Fabrication of intermediate products and finished sectors			
8. General flow structure and links		- **All flows within the 'Fabrication of Intermediate Products' and 'Finished Sectors' sections in Figure 1 have been estimated through a mass-balancing exercise based on the data and assumptions shown in items 8 ('General flow structure and links), 9 ('Finished sector distribution'), 10 ('Carbide product distribution') and 11 ('Manufacturing processing losses') of this list.** - The flow structure and links depicted in the intermediate section ('Fabrication of intermediate products') have been based on previous work by Smith (24) and a subsequent adaptation of the same work by Harper and Graedel (13), 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 ammonium paratungstate (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.	[Harper and Graedel, 2008; Smith, 1994]
Key assumptions:			
- Raw tungsten converted to APT	65 kt	70-80% suggested in literature (23). Assumed at 73% in this paper.	[Lassner and Schubert, 1999]
- Share of total tungsten powder used to produce tungsten carbide	47.9 kt	70-80% suggested in literature (23). Assumed at 70% in this paper.	[Lassner and Schubert, 1999]
9. Finished sector distribution			
- Tungsten chemicals	5.4 kt (6%)	Considering a total consumption of 95 kt of tungsten in 2010 (76.9 kt virgin tungsten + 24 kt scrap input – 5.9 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) based on sector distribution data from the British Geological Survey (25) and the International Tungsten Industry Association (26, 27).	[BGS, 2011; ITIA, 2011c]
- Tungsten mill products	11.7 kt (13%)		[BGS, 2011]
- Steel and alloys	24.4 kt (27%)		BGS, 2011
- Carbide products	48.7 kt (54%)		[BGS, 2011; ITIA, 2010]
10. Carbide product distribution			
- Metal cutting	10.7 kt (22%)	Product distribution data from the International Tungsten Industry Association (ITIA).	[ITIA, 2010]

Data categories	Values	Key sources and/or assumptions	References
- Stoneworking	12.7 kt (26%)		[ITIA, 2010]
- Wood and plastic working	12.7 kt (26%)		[ITIA, 2010]
- Chipless forming	4.4 kt (9%)		[ITIA, 2010]
11. Manufacturing processing losses			
- APT production losses	2.6 kt (4%)	Data on estimated intermediate product manufacturing losses has been obtained from consultation with industry specialists (17, 18) and the work of Smith (24).	[BGS, 2012; WBH, 2013; Smith, 1994]
- Metal powder manufacturing	0.6 kt (1%)		[BGS, 2012; WBH, 2013; Smith, 1994]
- Metal powder to tungsten carbide losses	0.1 kt (1%)		[BGS, 2012; WBH, 2013; Smith, 1994]
- Tungsten concentrate to carbide losses	0.4 kt (4%)		[BGS, 2012; WBH, 2013; Smith, 1994]
- Tungsten chemicals production losses	0.2 kt (4%)		[BGS, 2012; WBH, 2013; Smith, 1994]
- Tungsten losses in the manufacturing of steels and alloys	0.8 kt (4-5%)		[BGS, 2012; WBH, 2013; Smith, 1994]
- Average mass loss for intermediate manufacturing stage	4.7 kt (5%)		[BGS, 2012; WBH, 2013; Smith, 1994]
D. Tungsten grades			
- Ore deposits	0.06-1.2% W (0.08-1.5% WO_3)	Based on data obtained from industrial reports and other literature sources.	[Lassner, 1995]
- Ore concentrate	12-60% W (15-75% WO_3)		[Lassner, 1995]
- Tungsten scrap grade	10-99% W		[Lassner, 1995]
- APT	~71% W		[GTP, 2015]
- Tungsten metal powder	>99% W		[THPP, 2014]
- Tungsten carbide powder	65-95% W		[USGS, 2011]

Data categories	Values	Key sources and/or assumptions	References
- Ferrotungsten	75-85% W		[ITIA, 2011d]
- Tungsten forms	>99% W		[THPP, 2015]
- Tungsten mill products	>99% W		[THPP, 2015]
- Carbide product grades	65-95% W		[USGS, 2011]
- High speed steels	0.03-20% W		[ITIA, 2011e]
- Tool steels			
- Cast steels			[ITIA, 2011e]
- Heavy metal alloys			[ITIA, 2011e]
- Superalloys			[Haynes, 2013]
- Heavy metal alloys	>90% W		[ITIA, 2011f]
E. Energy consumption			
A detailed breakdown of energy consumptions is presented in Table 2 of the main text.			

References

Achzet, B., Reller, A. and Zepf, V. (University of Augsburg), Rennie C. (BP), Ashfield M. and Simmons J. (ON Communication). 2011. Materials critical to the energy industry. An introduction.

Almonty. 2012. Almonty Industries Inc. http://almonty.com/_resources/presentation/Almonty_05_12_Presentation.pdf (accessed 07 12, 2013).

APS-MRS. 2011. Energy critical elements: securing materials for emerging technologies. A report by the American Physical Society panel on public affairs and the Materials Research Society. Washington D.C.

BGS. 2011. Tungsten Profile. Keyworth, UK: British Geological Survey, Natural Environment Research Council, 2011.

BGS. 2012. "Understanding the tungsten lifecycle in Europe." Workshop organised by the British Geological Survey. London, UK, December 5, 2012.

ECJRC. 2011. Critical metals in strategic energy technologies. European Commission Joint Research Centre, Institute for Energy and Transport. Netherlands.

European Commission. 2014. Report on critical raw materials for the EU. Report of the Ad-hoc working group on defining critical raw materials.

Fromer, N., Eggert, R.G., and Lifton, J. 2011. Critical materials for sustainable energy applications. Resnick Institute.

GTP. 2015. "Global Tungsten and Powders Corp." Tungsten Chemicals. http://www.globaltungsten.com/en/products-services_tungsten-chemicals.htm (accessed January 30, 2015).

Harper, EM, and TE Graedel. 2008. "Illuminating Tungsten's Life Cycle in the United States: 1975-2000." (Environmental Science and Technology) 42: 3835–3842.

Haynes. 2013. Haynes International Inc. http://www.haynesintl.com/CRAlloys.htm (accessed 03 04, 2014).

ITIA. 2010. Cemented Carbides - A Success Story. International Tungsten Industry Association. June 2010. http://www.itia.info/assets/files/Newsletter_2010_06.pdf (accessed 01 14, 2013).

ITIA. 2011a. Tungsten supply and demand. International Tungsten Industry Association. http://www.itia.info/supply-and-demand.html (accessed 01 14, 2013).

ITIA. 2011b. Primary Uses of Tungsten. International Tungsten Industry Association. http://www.itia.info/tungsten-primary-uses.html (accessed 01 14, 2013).

ITIA. 2011c. Tungsten Chemicals and their Applications. International Tungsten Industry Association. June 2011. http://www.itia.info/assets/files/newsletters/Newsletter_2011_06.pdf (accessed 01 14, 2013).

ITIA. 2011d. Ferro-Tungsten and Melting Base. International Tungsten Industry Association. http://www.itia.info/ferro-tungsten-melting-base.html (accessed January 30, 2015).

ITIA. 2011e. Tungsten in Steel. International Tungsten Industry Association. http://www.itia.info/tungsten-in-steel.html (accessed 01 14, 2013).

ITIA. 2011f. Tungsten Heavy Metal Alloys. International Tungsten Industry Association. http://www.itia.info/tungsten-heavy-metal-alloys.html (accessed 01 14, 2013).

Lassner, E. 1995. "From tungsten concentrates and scrap to highly pure ammonium paratungstate (APT)." (Int. J. of Refractory Metals & Hard Materials) 13: 35-44.

Lassner, E, and W Schubert. 1999. Tungsten. New York, USA: Kluwer Academic/Plenum Publishers.

NATC. 2013. North American Tungsten Corporation Ltd. http://www.natungsten.com/s/Cantung.asp (accessed 07 12, 2013).

REKTN. 2008. Material Security - Ensuring Resource Availability for the UK Economy. Report prepared by Morley, N. and Eatherley, D., Oakdene Hollins Ltd, for the Resource Efficiency Knowledge Transfer Network.

Smith, G.R. 1994. Material Flow of Tungsten in the United States. US Department of the Interior.

THPP. 2014. Tungsten Heavy Powder and Parts. Tungsten powder specs. http://www.tungstenheavypowder.com/Tungsten_Heavy_Powder/Tungsten_Heavy_Powder_Products/tungsten_heavy_powder_products.html (accessed January 30, 2015).

UNEP. 2009. Critical metals for future sustainable technologies and their recycling potential. Report prepared by Buchert, M., Schüler, D. and Bleher, D., Öko-Institut.

USDOE. 2010. Critical Material Strategy. Advanced research Projects Agency-Energy. US Department of Energy.

USGS. 2011. Tungsten recycling in the United States in 2000. US Geological Survey Circular 1196-R. http://pubs.usgs.gov/circ/circ1196-R (accessed 02 02, 2013).

USNRC. 2007. Minerals, Critical Minerals, and the US Economy. US National Research Council, the National Academies Press, Washington D.C.

WBH. 2013. "Visit to Wolfram Bergbau und Hütten, Mittersill tungsten mine." Mittersill, Austria.