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Refractory metals - End-of-Life Resources

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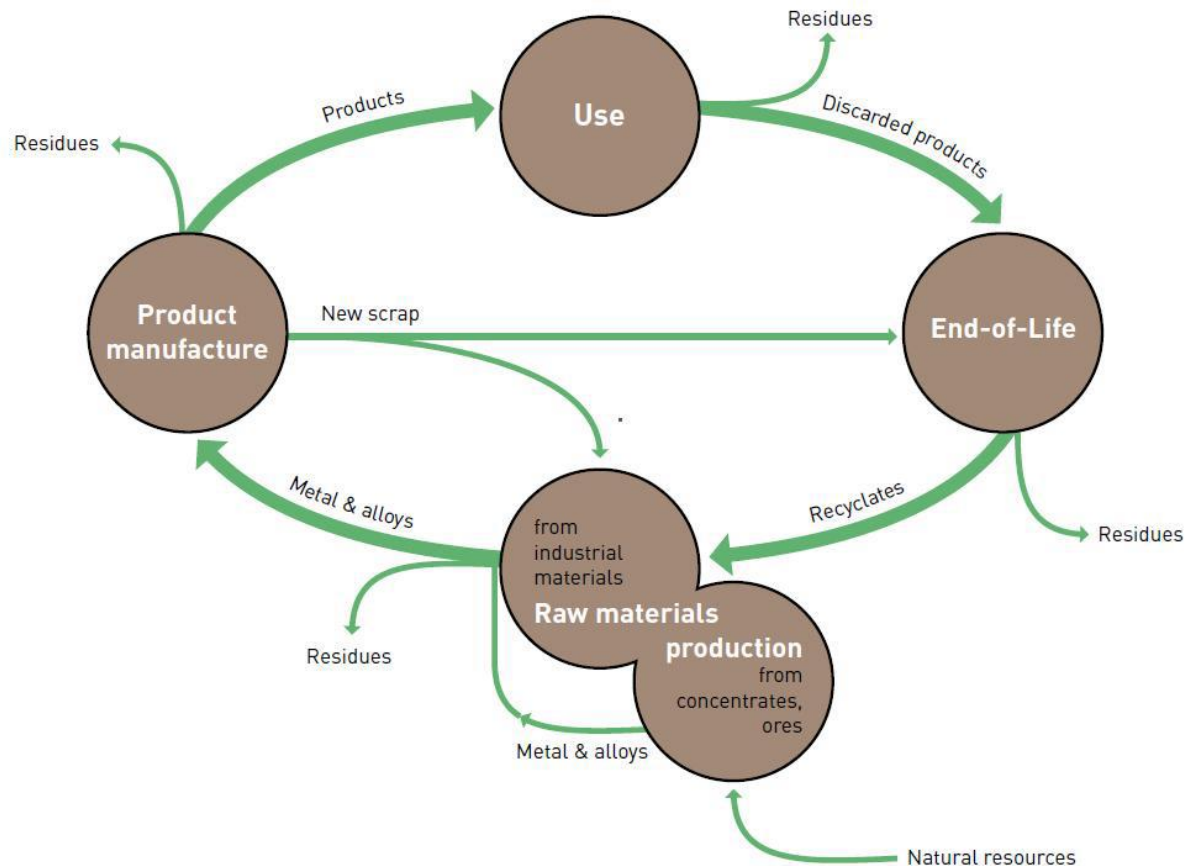
Content

- Introduction and objectives
- End-of-life streams
 - Molybdenum
 - Niobium
 - Rhenium
 - Tungsten
 - Tantalum
- Summary

Introduction and objectives

- The project aims for providing key information at policy, technical and market level to stakeholders along the refractory metals (molybdenum, niobium, tantalum, tungsten and rhenium) value chain in order to strengthen European market as well as establishing a multi-stakeholder platform supporting the refractory metals sector in Europe.
- The aim of this work was to identify the end-of-life waste products (urban mine) and their components containing refractory metals, estimate their quantities and form in the products in the limits of the available data, to identify the existing collection infrastructures and the incentives for delivery of waste products to legal operators.

Simplified metal and production lifecycle



Molybdenum, uses

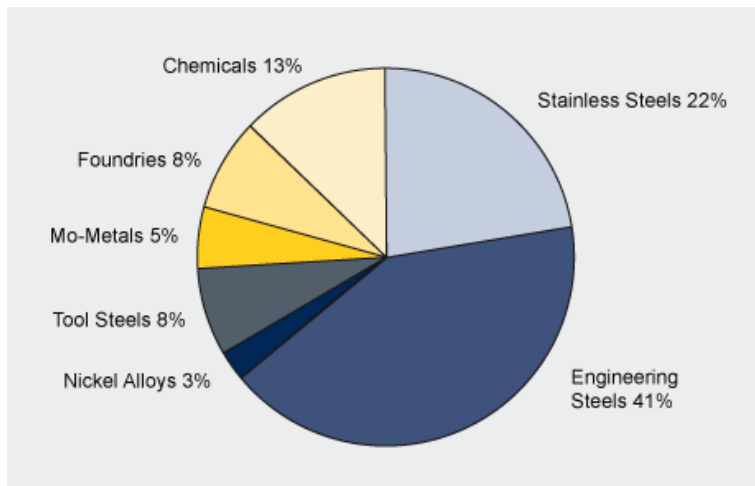


Figure: End-use of primary Mo (IMO, 2015)

- Global consumption 310 000 tons/a
- About 80 000 tons/a recycled

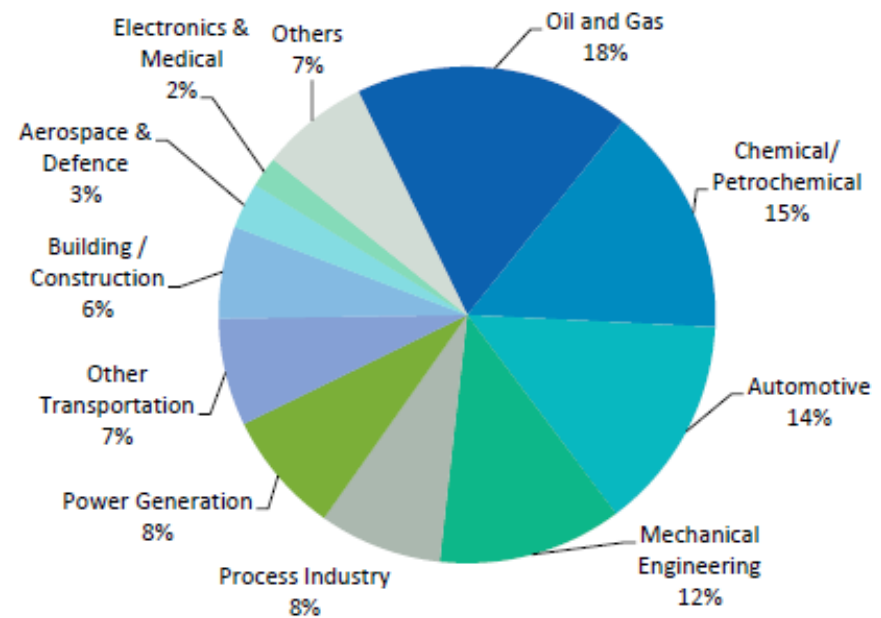


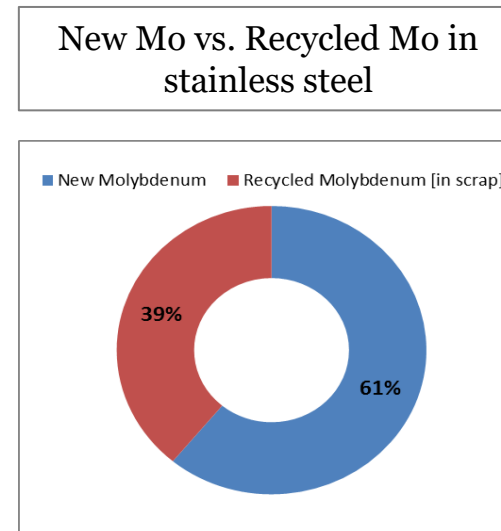
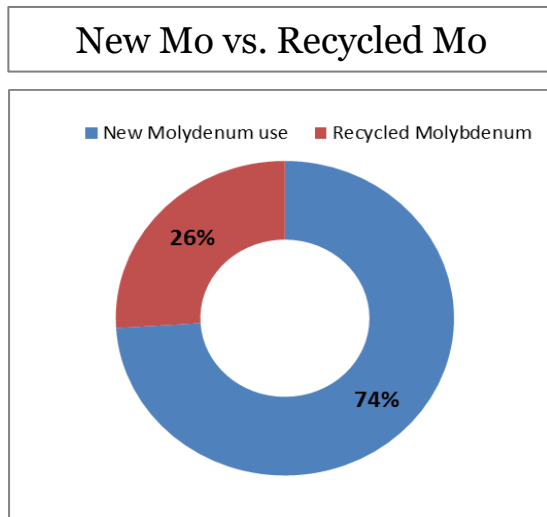
Figure: End-use of Mo from all sources (SMR GmbH 2011)

Molybdenum - end-of-life

Applications	End use sector	Share of consumption (global), %	Recycling
Steels	Automotive	14	<ul style="list-style-type: none"> • Relatively high collection rates • Due to losses, long lifetimes (15-50 a) and consumption growth, share of recycling < 30% of consumption • All the recycling is not functional
	Other transportation	7	
	Chemical + oil & gas	15	
	Mechanical engineering	12	
	Energy	8	
	Process industry	8	
	Construction	6	
Cast iron	Automotive, transport		Losses in ELV collection
Catalysts	Petrochemical industry	18	Several catalyst recycling companies, recycling rates n.a.
	Oil and gas		
Other	Electrics & Medical	2	Mostly very low recycling rates
	Aeordpace & defence	3	
	Lubricants		
	Pigments in plastics		

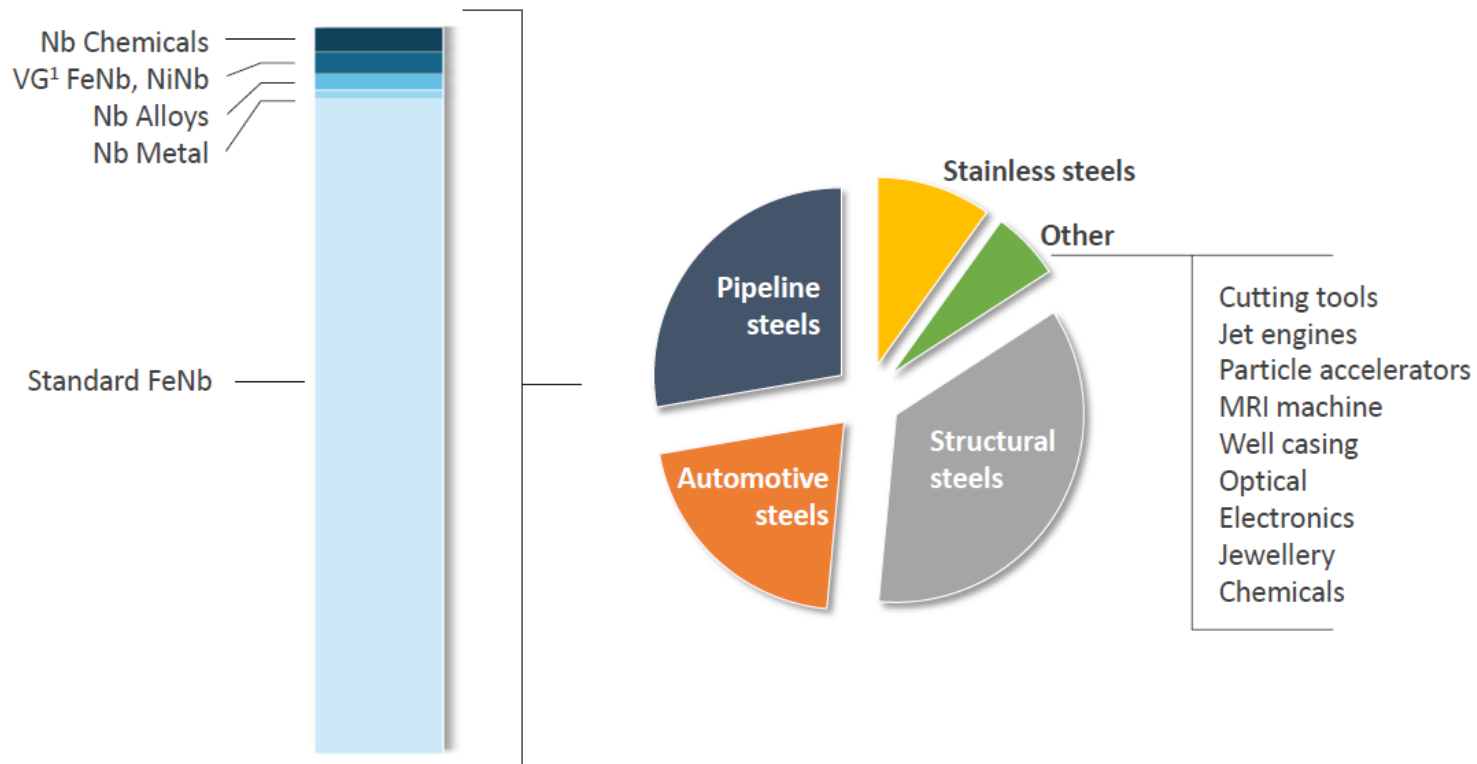
Molybdenum -recycling and losses

- Mainly used in steels (80%) and catalysators (14%)
 - In Europe about 30,000 tons/y Mo was functionally recycled



- Losses:
 - During the use losses due to corrosion, wearing and discard
 - Down-grading of Mo to steel qualities where its functionality is lost

Uses of Niobium



- Global consumption (2011) ~80 000 tons/y
- EU consumption ~24% of global consumption ~19 000 tons/y

Recycling of Niobium

Applications	End use sector	Share of consumption (global), %	Recycling
HSLA Steels	Construction	31	<ul style="list-style-type: none"> No specific recycling of Nb Functionality is partly lost when recycled with steels and alloys
	Automotive	28	
	Oil and gas pipelines	24	
	Chemical industry	3	
Superalloys	Aircraft industry	8	
	Nuclear industry		
Other	Superconducting magnets	6	Limited
	Electronics		No recycling
	Cutting tools		Limited

- About 20% of consumption of primary Nb is compensated by recycling (~4000 tons in Europe)
- About 400 – 580 tons/y Nb available in ELV in EU
- No data found about other application areas

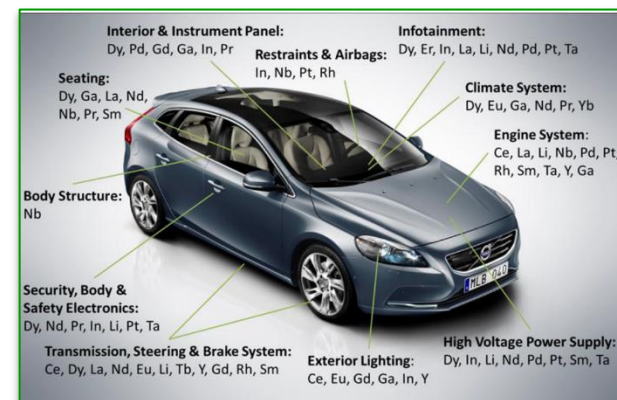
Source: European Commission Report on Critical Raw Materials for the EU, 2014;
British Geological Survey (BGS), 2011; Cullbrand and Magnussen, 2012

Refractory metals in ELV

Metal	Components	Quantity, g/vehicle ¹	Estimated total in scrapped ² cars, tonnes 2012	Fate
Molybdenum	Body: HS steels	500-630	3200 -4030	Recycled with steel, The rest ends to slag and residues
Niobium	Body: HSLA steel	63-90	400-580	
Tantalum	High-perf. electronics (engine, power supply and safety systems, etc.)	5.8-11	37-70	Ends to residual fractions and slags
Tungsten	Alloys	N.A (minor)	N.A	

¹Andersson, et al. 2016; Cullbrand and Magnussen 2012, ²Eurostat

- 6.3 million cars scrapped in EU27 + Norway in 2012 (Eurostat)
- A significant part of ELV leaks from EU statistics (scrapped by non-compliant actors or exported)
- Mo, Nb and Ta used in other transportation vehicles, as well



Rhenium

Applications	End use sector	Consumed tons /y, global 2012	Recycling	Available for recycling in Europe*
Superalloys (3-6% Re)	Aerospace: jet engines	45	Low rates	6 tons/a
Catalysts	Petroleum industry: reforming catalysts	5	High rates	1 ton/a
Other	Medical, tools, etc.	4	n.a.	n.a.

* Manufacturing and EoL waste that is currently not recycled

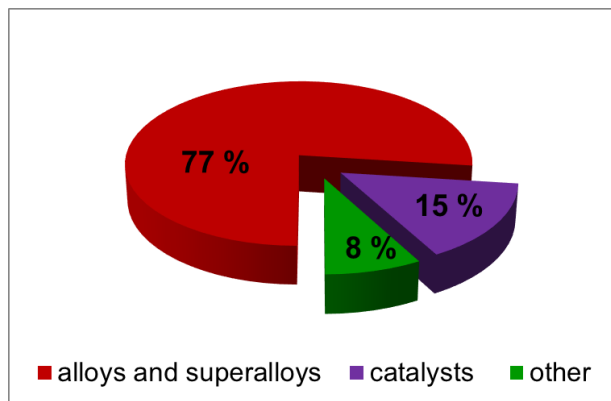


Figure: Global rhenium demand

- Global production of Re 50-60 tons/y
- About 7 tons/a recycled, most of it by European actors
- Losses due to wear, discard and non-functional recycling

Tungsten, W

- Global consumption ~83 kt/a
 - ~30% recycled scrap
- Estimates of total recycling rates vary from 30 to 40% of total waste (new scrap and EoL waste)
- Share of new scrap about 10% of total consumption of W*
- Recycling rate of new scrap is significantly higher than that of EoL waste
- Losses of EoL waste due to:
 - Dissipative uses
 - Losses during use, e.g. wear of tools
 - Lack of collection systems
 - Dilution to steels without using the functionalities

* Roskill 2010

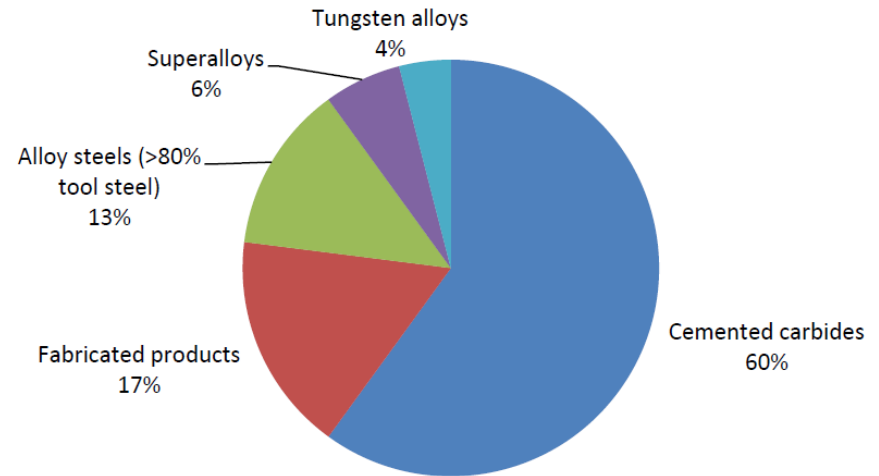


Figure: End-use of W (EC, 2010)

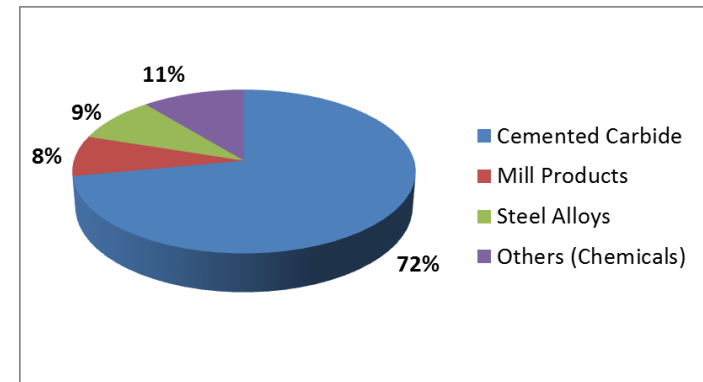


Figure: End-use of primary W in Europe 2010 (ITIA)

Tungsten - end-of-life

End use sector	Applications	Estimated recycling rate of EoL waste
Metal working machinery and equipment	Hard metal cutting tools, drills, saw blades	50%
Mining and construction machinery and equipment	Hard metal drilling and boring tools, inserts in tools	15%
Catalysts and other chemicals	Ni-W catalysts	N.A.
Lamps and lighting	Incandescent and discharge bulbs	Negligible
Transportation Industrial and Marine turbines	HS steel and superalloys: <ul style="list-style-type: none"> • Aircraft engine parts • Gas turbines 	80-90, non-functional

- About 30-40% of W in EoL products is currently recycled in Europe
- Several European recyclers

Tantalum, Ta

Key application areas

- *Consumer applications, particularly electronics*
- *Industrial and medical applications*
- *Estimated global consumption 1 500 – 2 000 tons/y (MMTA)*
- *Estimated EU consumption ~400 tons/y (20% of total)*

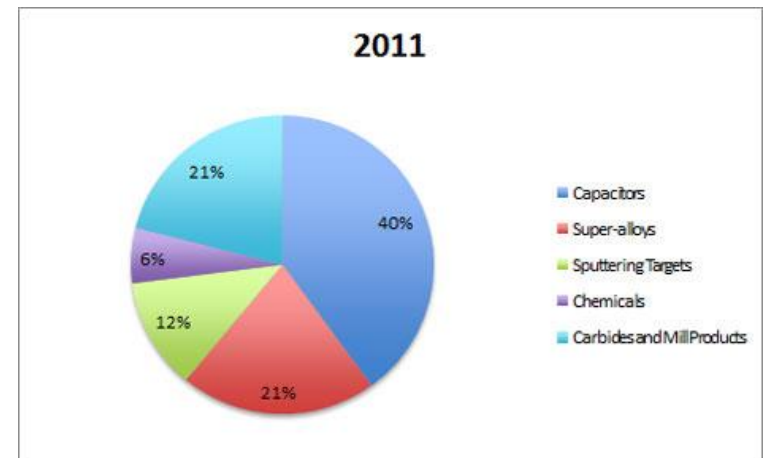


Figure: Demand of Ta in 2011

Tantalum, Ta

Applications	Share of consumption (global), %	End-use sector/end-of-life waste	EU recycling rate of Ta
Electronics - Capacitors - Sputtering targets - Other	40 20	Vehicles/ELV Aerospace and Military/metal scrap Portable electronics, TVs/WEEE Medical appliances Tele/datacom infra/WEEE	Recycling rate of Ta in electronics < 1% Recycling rates of end products are considerably higher
Cemented carbides (TaC)	13	Hard metal cutting and boring tools (with WC, TiC)	A part (25-50%) recycled with WC and TiC
Ta-based alloys pure Ta, Ta+W	8-11	Chemical process equipment Cathodic protection High temp. furnace parts Prosthetic devices	No data found, Recyclers exist
Ta superalloys (Ni, 3-12% Ta)	10-15	Air and land based turbines, Rocket nozzles	Recycled to low value mill products

Ta in EoL waste is mostly lost

- 60% of total used in high-performance electronics in EEE, vehicles, aircraft & military, medical
 - Estimated quantities of Ta available in the EU annually 40-70 tons in ELV and 70- 150 tons in WEEE
 - No economically viable methods for separation of Ta containing components from WEEE and ELV
 - Lost almost totally (~99%) in recycling stage
- Other uses: Ta alloys and superalloys, hard metals
 - During the use losses due to wear and discard
 - Superalloys mostly down-graded
 - Ta alloys and hard metals – a part is functionally recycled

Estimated global consumption and EoL scrap collection rates of refractory metals

	Consumption Global, tons/y	Average recycled content, %	Available for recycling in EU EoL scrap, tons/y
Molybdenum	310 000	25-50	
Niobium	~80 000 Primary 63 000	> 50	10 000 – 15 000
Rhenium	50-60	10-25	<10
Tantalum	1 500 -2 000	<1 (electronics) 10-25 (other)	300 -350
Tungsten	83 000	25-50	<15

Summary - recycling of key EoL products

- Steels and alloys: Mo, Nb, Ta, W, Re
 - Relatively high collection rates, a part is down-graded (functionality lost)
- ELV and other transportation: Mo, Nb, Ta (W, Re)
 - Losses due to export and non-compliant treatment
 - Mo and Nb recycled, Ta lost
- WEEE: Ta, W, (Nb, Mo)
 - Gaps in statistics, losses due to export
 - Ta and W are not recycled
- Hard metals: W, Ta
 - Relatively high recycling rates (higher for W)
- Catalysts: Mo, W, Re
 - Recyclers exist, recycling rates ?