Supplementary material for

Environmental Life Cycle Assessment of Cemented Carbide (WC-Co) Production

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1. Data for life cycle inventory calculations and sensitivity analysis

Table S1. Parameters applied in life cycle inventory calculations and values used in the sensitivity analysis. Note that sensitivity analysis was conducted using the low environmental impact case (LC) and high environmental impact case (HC) values for parameters with ranges available. Only parameters for which no ranges were available were tested in the sensitivity analysis applying ±50% of the baseline case (BC) value. The references are given for the data applied in the BC, LC and HC. *Note that stochiometric efficiencies and recoveries cannot exceed 100%. **Note that four times the value for this parameter is needed for the washing. ***Note that when the share of a specific content in the organic solvent is changed, the shares of the other contents also need to be changed, and this was done according to their relational shares in the baseline case, so that the sum always is 100%. APT=ammonium paratungstate, WC=tungsten carbide and WC-Co=tungsten carbide with cobalt.

Parameter [unit]	BC	LC	HC	-50% of BC value	+50% of BC value	References
MINING						
Energy use, scheelite concentrates [kWh electricity and diesel/ton ore]	31.7	31.7	31.7	15.85	47.55	Leal-Ayala et al. (2015)
Energy use, wolframite concentrates [kWh electricity and diesel/ton ore]	31.7	31.7	31.7	15.85	47.55	Assumption by authors based on data on energy use in scheelite mining from Leal-Ayala et al. (2015)
Share of energy that is diesel in U.S. metals mining [%] (rest is electricity)	73	46	100	-	-	USDoE (2007)
Gravity methods and grinding process						
Tungsten content in workable ores [%]	0.5	0.6	0.4	-	-	Lassner et al. (2000), Wolfe et al. (2014)
Share of the mixture that is water [%]	25	20	30	-	-	Yih and Wang (1979)
Tungsten yield, scheelite ore [%]	75	90	60	-	-	Lassner et al. (2000)
Tungsten yield, wolframite ore [%]	75	90	60	-	-	Assumption by authors based on data on yields for scheelite ores from Lassner et al. (2000)
Tungsten concentration in wolframite concentrates [%]	52	53	42	-	-	Wolfe et al. (2014)
Low tungsten concentration fraction, scheelite [%]	0.41	0.41	0.41	0.205	0.615	Martins and Amarante (2013)
High tungsten concentration fraction, scheelite [%]	57	58	56	-	-	Wolfe et al. (2014)
Scheelite output that is in the high concentration fraction [%]	60	60	60	30	90	Martins and Amarante (2013), Yih and Wang (1979)

Parameter [unit]	BC	LC	HC	-50% of BC value	+50% of BC value	References
Sulfide and scheelite flotations						
Water share of slurry [%]	62.5	60	65	-	-	Yih and Wang (1979), Martins and Amarante (2013)
Anyl xanthate [g/ton slurry]	20	20	20	10	30	Martins and Amarante (2013)
Sodium sulfide [g/ton slurry]	500	500	500	250	750	
Pine oil [g/ton slurry]	4	4	4	2	6	
Sodium carbonate [g/kg ore]	3.49	0.48	6.5	-	-	Yih and Wang (1979)
Sodium silicate [g/kg ore]	2.38	1	3.75	-	-	
Tannin [g/kg ore]	0.4	0.05	0.75	-	-	
Sodium cyanide [g/kg ore]	0.28	0.05	0.5	-	-	
Oleic acid [g/kg ore]	0.7	0.4	1	-	-	
Pine oil [g/kg ore]	0.06	0.025	0.09	-	-	
Tungsten yield in scheelite flotation [%]	85	90	80	-	-	Lassner et al. (2000)
TRANSPORT						
Road distance [km]	5000	5000	5000	2500	7500	Assumption by the authors using the approximate distance between the Cantung mine in Canada and WC-Co production plant in Cleveland, Ohio.
HYDROMETALLURGY						
Energy use, production of APT from concentrates [kWh/kg APT]	1.3	1	1.6	-	-	EC (2001), Wang et al. (1995)
Sodium carbonate and hydroxide digestions with subsequent filtration						
Concentration of sodium carbonate solution [%]	14	10	18	-	-	Lassner et al. (2000)
Molar ratio between sodium carbonate and tungsten [-]	3.5	2.5	4.5	-	-	
Concentration of sodium hydroxide solution [%]	8.5	7	10	-	-	
Molar ratio between sodium hydroxide and tungsten [-]	1.05	1.05	1.05	0.525	1.575	
Tungsten yield in sodium hydroxide digestion [%]	98	99	97	-	-	Lassner and Schubert (1999)
Silica and molybdenum precipitations						
Addition of aluminum sulfate solution [kg/kg tungsten]	0.1	0.1	0.1	0.05	0.15	Lassner and Schubert (1999)
Addition of magnesium sulfate solution [kg/kg tungsten]	0.04	0.04	0.04	0.02	0.06	
Molybdenum content in scheelite concentrates [%]	1	0	2	-	-	Lassner and Schubert (1999), Yih and Wang (1979)
Molybdenum content in wolframite concentrates [%]	0.0015	0	0.003	-	-	

Parameter [unit]	BC	LC	HC	-50% of BC value	+50% of BC value	References
Addition of sodium hydrosulfide in stochiometric requirement of Reaction 3 (R3) in article [-]	2.25	2	2.5	-	-	Wolfe et al. (2014)
Stochiometric efficiency in reactions with sulfuric acid [%]	95	95	95	47.5	100*	Hischier et al. (2005)
Wash of filtration cake [kg water/kg solid filtration cake] **	2.3	2.3	2.3	1.15	3.45	Yih and Wang (1979)
Solvent extraction						
Input organic solvent [kg/kg tungsten]	40	40	40	20	60	Yih and Wang (1979)
Share of organic solvent that is alamine 336 [%]***	7.3	7.3	7.3	3.6	11	
Share of organic solvent that is decanol [%]***	7.4	7.4	7.4	3.7	11	
Share of organic solvent that is kerosene [%]***	85	85	85	42	100*	
Input 5% sulfuric acid solution [kg/kg tungsten]	3.2	3.2	3.2	1.6	4.8	
Input deionized water [kg/kg tungsten]	8.5	8.5	8.5	4.3	13	
Input 5% ammonia solution [kg/kg tungsten]	12	12	12	6	18	
Recovery of organic solvent [%]	95	95	95	47.5	100*	Geisler et al. (2004)
Fugitive loss of ammonia to air [%]	2	2	2	1	3	Jiménez-González et al. (2000)
Crystallization						
Recovery of ammonia [%]	61	99	23	-	-	Ashtari et al. (2016)
PYROMETALLURGY						
Energy use, production of WC from APT [kWh/kg WC]	7.75	3.5	12	-	-	EC (2001)
Hydrogen reduction						
Stochiometric excess hydrogen [-]	21.25	2.5	40	-	-	Lassner and Schubert (1999), Wolfe et al. (2014)
Fugitive loss of hydrogen emitted to air [%]	0.5	0.5	0.5	0.25	0.75	Jiménez-González et al. (2000)
Carburization						
Carbon content in WC powder [%]	6.13	6.13	6.13	3.07	9.2	Yih and Wang (1979)
Excess of carbon [%]	6	2	10	-	-	
Stochiometric efficiency of the input of hydrogen [%]	95	95	95	47.5	100*	Hischier et al. (2005)
Fugitive loss of hydrogen emitted to air [%]	0.5	0.5	0.5	0.25	0.75	Jiménez-González et al. (2000)
POWDER METALLURGY						
Energy use, production of WC-Co from WC [kWh/kg WC-Co]	11	2	20	-	-	Kruzhanov and Arnhold (2012)

Parameter [unit]	BC	LC	HC	-50% of BC value	+50% of BC value	References
Powder milling						
Share of WC and cobalt powder in the mixture [%]	50	50	50	25	75	Fauchais et al. (2014)
Cobalt content of the WC and cobalt powder share [%]	11	16	6	-	-	Fang et al. (2014)
Paraffin share of the mixture [%]	2	1	3	-	-	Lassner and Schubert (1999)
Fugitive loss of heptane and hexane [%]	1	1	1	0.5	1.5	Jiménez-González et al. (2000)
Granulation and compaction with subsequent sintering						
Flow of nitrogen gas per total cross-section of the chamber [m/s]	0.4	0.3	0.5	-	-	Neikov (2009)
Capacity of spray drier for WC-Co production [kg/h]	150	180	120	-	-	Lassner and Schubert (1999)
Diameter of drier [m]	2	2	2	1	3	
Fugitive loss of nitrogen emitted to air [%]	0.5	0.5	0.5	0.25	0.75	Jiménez-González et al. (2000)
Recovery of organic solvent [%]	95	95	95	47.5	100*	Geisler et al. (2004)
Yield of WC and cobalt powder (also containing paraffin) [%]	97.5	100	95	-	-	Lassner and Schubert (1999), Mehrotra (2014)
RECYCLING						
Share of total recycling via zinc recycling [%]	50	50	50	25	75	Leal-Ayala et al. (2015)
Chemical recycling						
Tungsten content in scrap [%]	67.5	95	40	-	-	Lassner and Schubert (1999)
Energy requirement in chemical recycling [kWh/kg tungsten processed]	6.5	2	11	-	-	Hairunnisha et al. (2007), Lassner and Schubert (1999)
Input of sodium hydroxide [kg/kg tungsten]	0.96	0.96	0.96	0.48	1.44	Hairunnisha et al. (2007)
Yield of tungsten [%]	95	100	90	-	-	
Zinc recycling						
Energy requirement in zinc recycling [kWh/kg WC and cobalt powder output]	2.75	1.5	4	-	-	Acharyulu and Rama Rao (1996), EC (2001)
Fugitive loss of zinc emitted to air [%]	0.5	0.5	0.5	0.25	0.75	Jiménez-González et al. (2000)
Yield of WC-Co in the zinc recycling process [%]	97.5	98	97	-	-	Upadhyaya (1998)
Zinc requirement [kg/kg WC-Co]	1.15	1	1.3	-	-	

2. Background system data

Table S2. Sources of the background system data. GLO=global, RoW=rest-of-the-world, CA-NT=Canada Northwest territories and NPCC, US only=Northeast power coordinating council, United States part only.

Data from the Ecoinvent database (2017)	
Parameter	**Ecoinvent dataset**
Input	
Aluminum sulfate	Aluminium sulfate production, powder [RoW]
Ammonia	Ammonia production, steam reforming, liquid [RoW]
Carbon black	Carbon black production [GLO]
Cobalt powder	Cobalt production [GLO]
Decanol	Modelled as fatty alcohol. Fatty alcohol production, petrochemical [RoW]
Diesel	Diesel, burned in building machine [GLO]
Electricity Canada (Northwest territories)	Electricity, high voltage, production mix [CA-NT]
Electricity US (Northeast)	Electricity, high voltage, production mix [NPCC, US only]
Heptane	Molecular sieve separation of naphtha [RoW]
Hexane	Molecular sieve separation of naphtha [RoW]
Hydrogen	Hydrogen cracking, APME [RoW]
Kerosene	Petroleum refinery operation [RoW]
Magnesium sulfate	Magnesium sulfate production [RoW]
Nitrogen	Air separation, cryogenic [RoW]
Oleic acid	Fatty acid production, from palm oil [RoW]
Paraffin	Paraffin production [RoW]
Sodium carbonate	Soda production, solvay process [RoW]
Sodium cyanide	Sodium cyanide production [RoW]
Sodium hydroxide	Chlor-alkali electrolysis, membrane cell [RoW]
Sodium hydrosulfide	Sodium hydrosulfide production [RoW]
Sodium silicate	Sodium silicate production, furnace process, solid product [RoW]
Sodium sulfide	Sodium sulfide production [GLO]
Sulfuric acid	Sulfuric acid production [RoW]
Water	Tap water production, conventional treatment [RoW]
Water (deionized)	Water production, deionised, from tap water, at user [RoW]
Transport lorry	Transport, freight, lorry >32 metric ton, EURO3 [RoW]
Zinc	Primary zinc production from concentrate [RoW]
Output	
Treatment of liquid aqueous waste	Treatment of wastewater, average, capacity 1E9l/year [RoW]
Treatment of liquid organic waste	Treatment of spent solvent mixture, hazardous waste incineration [RoW]
Treatment of solid waste (landfill)	Process-specific burdens production, inert material landfill [RoW]

Treatment of tailings (non-sulfidic)	Treatment of non-sulfidic tailing, off-site [GLO]	
Treatment of tailings (sulfidic)	Treatment of sulfidic tailing, off-site [GLO]	
Data from other sources		
Parameter	**Comment**	**Reference**
Input		
Alamine 336	LCI data provided by other reference. Ecoinvent used for LCIA.	Vahidi and Zhao (2017) and Ecoinvent database (2017)
Anyl xanthate	Not included due to negligible amount	-
Frother	Not included due to negligible amount	-
Pine oil	Not included due to negligible amount	-
Tannin	LCIA data for some midpoint indicators provided by the reference.	Ding et al. (2017)

3. Unit process data results

Note that chemical recycling is intertwined with the hydrometallurgy phase and can be conducted via the scheelite or wolframite route, see Table S9 and Table S10.

Table S3. Mining (scheelite). All values are in kg per kg of scheelite concentrate unless otherwise noted. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Main input	Scheelite ore	160	110	250	(Extraction, crushing and milling)
Input	Energy - diesel	13	5.9	29	MJ/kg scheelite concentrate. (Mining)
Input	Energy - electricity	1.4	1.9	0	kWh/kg scheelite concentrate. (Mining)
Input	Water	54	28	110	(Gravity methods and grinding)
Input	Water	99	89	110	(Sulfide flotation)
Input	Sulphide flotation reagents. consisting of:	0.083	0.078	0.089	(Sulfide flotation)
	Sodium sulfide	0.079	0.074	0.085	
	Anyl xanthate	0.0032	0.0030	0.0034	
	Pine oil	0.00063	0.00059	0.00068	
Input	Scheelite flotation reagents. consisting of:	0.43	0.12	0.74	(Scheelite flotation)
	Sodium carbonate	0.21	0.028	0.38	
	Sodium silicate	0.14	0.059	0.22	
	Tannin	0.024	0.0029	0.044	
	Sodium cyanide	0.016	0.0029	0.030	
	Oleic acid	0.041	0.023	0.059	
	Frother	0.0034	0.0015	0.0053	
Output	Separated material. consisting of:	100	53	190	Assume that this is tailings. Base case: Half non-sulfidic and half sulfidic. LS: non-sulfidic. HS: sulfidic. (Gravity methods and grinding)
	Gangue	100	53	190	
	Tungsten loss	0.20	0.067	0.41	
Output	Separated material. consisting of:	58	58	59	Assume that this is tailings. Base case: Half non-sulfidic and half sulfidic. LS: non-sulfidic. HS: sulfidic. (Sulphide and scheelite flotation)
	Tungsten lost	0.036	0.024	0.049	
	Gangue	58	58	59	
Output	With the separated material. separated reagents. consisting of:	0.47	0.17	0.77	(Sulfide and scheelite flotation)
	Sodium sulfide	0.079	0.074	0.085	
	Anyl xanthate	0.0032	0.0030	0.0034	
	Sodium carbonate	0.21	0.028	0.38	
	Sodium silicate	0.14	0.059	0.22	
	Tannin	0.024	0.0029	0.044	
	Sodium cyanide	0.016	0.0029	0.030	
	Frother	0.0034	0.0015	0.0053	
Output	Carbon dioxide	0.12	0.068	0.17	Assume this is an emission to air. (Roasting)
Main output	Scheelite concentrate	1.0	1.0	1.0	(Roasting)

Table S4. Mining (wolframite). All values are in kg per kg of wolframite concentrate unless otherwise noted. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Main input	Wolframite ore	140	98	180	(Extraction, crushing and milling)
Input	Energy - diesel	12	5.2	20	MJ/kg wolframite concentrate. (Mining)
Input	Energy - electricity	1.2	1.7	0	kWh/kg wolframite concentrate. (Mining)
Input	Water	46	25	75	(Gravity methods and grinding)
Output	Separated material, consisting of:	140	97	170	Assume that this is tailings. Base case: Half non-sulfidic and half sulfidic. LS: non-sulfidic. HS: sulfidic. (Gravity methods and grinding)
	Gangue	140	97	170	
	Tungsten loss	0.17	0.059	0.28	
Main output	Wolframite concentrate	1.0	1.0	1.0	(Gravity methods and grinding)

Table S5. Transport. All values are in ton·km per kg of tungsten concentrates. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Input	Transport by lorry	5.0	5.0	5.0	(Transport)

Table S6. Hydrometallurgy (scheelite). All values are in kg per kg of ammonium paratungstate (APT) unless otherwise noted. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Main input	Scheelite concentrate	1.2	1.2	1.3	(Sodium carbonate digestion)
Input	Sodium carbonate solution. consisting of:	10	10	10	(Sodium carbonate digestion)
	Sodium carbonate	1.4	1.0	1.8	
	Water	8.7	9.1	8.3	
Input	Aluminum sulfate solution. consisting of:	0.071	0.071	0.071	(Silica precipitation)
	Aluminum sulfate	0.036	0.036	0.036	
	Water	0.035	0.035	0.035	
Input	Magnesium sulfate solution. consisting of:	0.027	0.027	0.027	(Silica precipitation)
	Magnesium sulfate	0.013	0.013	0.013	
	Water	0.014	0.014	0.014	
Input	Sodium hydrosulfide	0.065	0	0.15	(Molybdenum precipitation)
Input	Sulfuric acid	0.53	0	1.46	(Molybdenum precipitation)
Input	Wash water	0.23	0	0.47	(Molybdenum precipitation)

Input	Alamine 336	0.10	0.10	0.10	(Solvent extraction)
Input	Decanol	0.10	0.10	0.10	(Solvent extraction)
Input	Kerosene	1.2	1.2	1.2	(Solvent extraction)
Input	Sulfuric acid solution. consisting of:	2.3	2.3	2.3	(Solvent extraction)
	Sulfuric acid	0.11	0.11	0.11	
	Water	2.2	2.2	2.2	
Input	Deionized wash water	6.0	6.0	6.0	(Solvent extraction)
Input	Ammonia solution. consisting of:	8.4	8.3	8.6	(Solvent extraction)
	Ammonia	0.18	0.013	0.34	
	Water	8.2	8.2	8.2	
Input	Electricity	1.3	1.0	1.6	kWh/kg APT. (Hydrometallurgy)
Output	Hydrogen sulfide	0.0044	0	0.0089	Assumed to be an emission to air. (Molybdenum precipitation)
Output	Molybdenum sulfide	0.025	0	0.050	Assumed to be solid waste. (Molybdenum precipitation)
Output	Wash water	0.23	0	0.47	Assumed to be liquid aqueous waste. (Molybdenum precipitation)
Output	Carbon dioxide	0.42	0.25	0.59	Assumed to be an emission to air. (Silica and molybdenum precipitation)
Output	Alamine 336	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Decanol	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Kerosene	1.2	1.2	1.2	Assumed to be liquid organic waste. (Solvent extraction)
Output	Ammonia gas	0.0089	0.0089	0.0089	Assumed to be emitted to air (solvent extraction)
Output	Deionized wash water	6.0	6.0	6.0	Assumed to be liquid aqueous waste. (Solvent extraction)
Output	Sodium sulfate	1.0	0.23	2.35	Assumed to be liquid aqueous waste. (Solvent extraction)
Output	Ammonia gas	0.099	0.0025	0.19	Assumed to be an emission to air. (Crystallization)
Output	Gangue	1.0	0.92	1.0	Assumed to be solid waste. (Hydrometallurgy)
Main output	APT	1.0	1.0	1.0	(Crystallization)

Table S7. Hydrometallurgy (wolframite). All values are in kg per kg of ammonium paratungstate (APT) unless otherwise noted. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	**Parameter**	**BC**	**LC**	**HC**	**Comment (process or phase)**
Main input	Wolframite concentrate	1.4	1.3	1.7	(Sodium hydroxide digestion)
Input	Sodium hydroxide solution. consisting of:	1.9	2.3	1.7	(Sodium hydroxide digestion)

	Sodium hydroxide	0.16	0.16	0.17	
	Water	1.8	2.2	1.5	
Input	Aluminum sulfate solution. consisting of:	0.071	0.071	0.071	(Silica precipitation)
	Aluminum sulfate	0.036	0.036	0.036	
	Water	0.035	0.035	0.035	
Input	Magnesium sulfate solution. consisting of:	0.027	0.027	0.027	(Silica precipitation)
	Magnesium sulfate	0.013	0.013	0.013	
	Water	0.014	0.014	0.014	
Input	Sodium hydrosulfide	0.00011	0	0.00030	(Molybdenum precipitation)
Input	Sulfuric acid	0.0051	0	0.010	(Molybdenum precipitation)
Input	Wash water	0.00039	0	0.0010	(Molybdenum precipitation)
Input	Alamine 336	0.10	0.10	0.10	(Solvent extraction)
Input	Decanol	0.10	0.10	0.10	(Solvent extraction)
Input	Kerosene	1.2	1.2	1.2	(Solvent extraction)
Input	Sulfuric acid solution. consisting of:	2.3	2.3	2.3	(Solvent extraction)
	Sulfuric acid	0.11	0.11	0.11	
	Water	2.2	2.2	2.2	
Input	Deionized wash water	6.0	6.0	6.0	(Solvent extraction)
Input	Ammonia solution. consisting of:	8.4	8.3	8.6	(Solvent extraction)
	Ammonia	0.18	0.013	0.34	
	Water	8.2	8.2	8.2	
Input	Electricity	1.3	1.0	1.6	kWh/kg APT. (Hydrometallurgy)
Output	Hydrogen sulfide	0.0000073	0	0.000018	Assumed to be an emission to air. (Molybdenum precipitation)
Output	Molybdenum sulfide	0.000041	0	0.00010	Assumed to be solid waste. (Molybdenum precipitation)
Output	Wash water	0.00039	0	0.0010	Assumed to be liquid aqueous waste. (Molybdenum precipitation)
Output	Carbon dioxide	0	0	0	Assumed to be an emission to air. (Silica and molybdenum precipitation)
Output	Alamine 336	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Decanol	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Kerosene	1.2	1.2	1.2	Assumed to be liquid organic waste. (Solvent extraction)
Output	Ammonia gas	0.0089	0.0089	0.0089	Assumed to be emitted to air (solvent extraction)
Output	Deionized wash water	6.0	6.0	6.0	Assumed to be liquid aqueous waste. (Solvent extraction)
Output	Sodium sulfate	0.23	0.23	0.24	Assumed to be liquid aqueous waste. (Solvent extraction)

Output	Ammonia gas	0.10	0.0025	0.19	Assumed to be an emission to air. (Crystallization)
Output	Gangue	0.55	0.44	0.97	Assumed to be solid waste. (Hydrometallurgy)
Main output	APT	1.0	1.0	1.0	(Crystallization)

Table S8. Chemical recycling process. All values are in kg per kg of impure sodium tungstate (Na_2WO_4) solution unless otherwise noted. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment
Main input	Tungsten scrap	0.61	0.52	0.72	
Input	Sodium hydroxide	0.39	0.48	0.28	
Input	Electricity	2.7	1.0	3.2	kWh/kg impure Na_2WO_4 solution
Main output	Impure Na_2WO_4 solution. of which:	1.0	1.0	1.0	
	Tungsten	0.39	0.50	0.26	Dissolved as Na_2WO_4
	Undissolved tungsten	0.020	0	0.029	Lost in subsequent filtration process
	Sodium hydroxide excess	0.21	0.26	0.15	Need to be neutralized later in the hydrometallurgy phase

Table S9. Hydrometallurgy (chemical recycling via the scheelite route). All values are in kg per kg of ammonium paratungstate (APT) unless otherwise noted. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Main input	Tungsten scrap	1.1	0.74	2.0	(Chemical recycling)
Input	Sodium hydroxide	0.71	0.68	0.75	(Chemical recycling)
Input	Aluminum sulfate solution. consisting of:	0.071	0.071	0.071	(Silica precipitation)
	Aluminum sulfate	0.036	0.036	0.036	
	Water	0.035	0.035	0.035	
Input	Magnesium sulfate solution. consisting of:	0.027	0.027	0.027	(Silica precipitation)
	Magnesium sulfate	0.013	0.013	0.013	
	Water	0.014	0.014	0.014	
Input	Sodium hydrosulfide	0.058	0	0.23	(Molybdenum precipitation)
Input	Sulfuric acid	0.29	0	0.66	(Molybdenum precipitation)
Input	Wash water	0.21	0	0.7	(Molybdenum precipitation)
Input	Alamine 336	0.10	0.10	0.10	(Solvent extraction)
Input	Decanol	0.10	0.10	0.10	(Solvent extraction)
Input	Kerosene	1.2	1.2	1.2	(Solvent extraction)
Input	Sulfuric acid solution. consisting of:	2.3	2.3	2.3	(Solvent extraction)
	Sulfuric acid	0.11	0.11	0.11	

	Water	2.2	2.2	2.2	
Input	Deionized wash water	6.0	6.0	6.0	(Solvent extraction)
Input	Ammonia solution. consisting of:	8.4	8.3	8.6	(Solvent extraction)
	Ammonia	0.18	0.013	0.34	
	Water	8.2	8.2	8.2	
Input	Electricity	6.1	2.4	10	kWh/ kg APT. (Hydrometallurgy)
Output	Hydrogen sulfide	0.0039	0	0.014	Assumed to be an emission to air. (Molybdenum precipitation)
Output	Molybdenum sulfide	0.022	0	0.078	Assumed to be solid waste. (Molybdenum precipitation)
Output	Wash water	0.21	0	0.73	Assumed to be liquid aqueous waste. (Molybdenum precipitation)
Output	Alamine 336	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Decanol	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Kerosene	1.2	1.2	1.2	Assumed to be liquid organic waste. (Solvent extraction)
Output	Ammonia gas	0.0089	0.0089	0.0089	Assumed to be emitted to air (solvent extraction)
Output	Deionized wash water	6.0	6.0	6.0	Assumed to be liquid aqueous waste. (Solvent extraction)
Output	Sodium sulfate	0.64	0.23	1.2	Assumed to be liquid aqueous waste. (Solvent extraction)
Output	Ammonia gas	0.10	0.0025	0.19	Assumed to be an emission to air. (Crystallization)
Output	Gangue	0.72	0.36	1.6	Assumed to be solid waste. (Hydrometallurgy)
Main output	APT	1.0	1.0	1.0	(Crystallization)

Table S10. Hydrometallurgy (chemical recycling via the wolframite route). All values are in kg per kg of ammonium paratungstate (APT) unless otherwise noted. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Main input	Tungsten scrap	1.1	0.74	2.0	(Chemical recycling)
Input	Sodium hydroxide	0.71	0.68	0.75	(Chemical recycling)
Input	Aluminum sulfate solution. consisting of:	0.071	0.071	0.071	(Silica precipitation)
	Aluminum sulfate	0.036	0.036	0.036	
	Water	0.035	0.035	0.035	
Input	Magnesium sulfate solution. consisting of:	0.027	0.027	0.027	(Silica precipitation)
	Magnesium sulfate	0.013	0.013	0.013	
	Water	0.014	0.014	0.014	
Input	Sodium hydrosulfide	0.000087	0	0.00034	(Molybdenum precipitation)
Input	Sulfuric acid	0.25	0	0.53	(Molybdenum precipitation)
Input	Wash water	0.00031	0	0.0011	(Molybdenum precipitation)

Input	Alamine 336	0.10	0.10	0.10	(Solvent extraction)
Input	Decanol	0.10	0.10	0.10	(Solvent extraction)
Input	Kerosene	1.2	1.2	1.2	(Solvent extraction)
Input	Sulfuric acid solution. consisting of:	2.3	2.3	2.3	(Solvent extraction)
	Sulfuric acid	0.11	0.11	0.11	
	Water	2.2	2.2	2.2	
Input	Deionized wash water	6.0	6.0	6.0	(Solvent extraction)
Input	Ammonia solution. consisting of:	8.4	8.3	8.6	(Solvent extraction)
	Ammonia	0.18	0.013	0.34	
	Water	8.2	8.2	8.2	
Input	Electricity	6.1	2.4	10	kWh/kg APT. (Hydrometallurgy)
Output	Hydrogen sulfide	0.0000058	0	0.000021	Assumed to be an emission to air. (Molybdenum precipitation)
Output	Molybdenum sulfide	0.000033	0	0.00012	Assumed to be solid waste. (Molybdenum precipitation)
Output	Wash water	0.00031	0	0.0011	Assumed to be liquid aqueous waste. (Molybdenum precipitation)
Output	Alamine 336	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Decanol	0.10	0.10	0.10	Assumed to be liquid organic waste. (Solvent extraction)
Output	Kerosene	1.2	1.2	1.2	Assumed to be liquid organic waste. (Solvent extraction)
Output	Ammonia gas	0.0089	0.0089	0.0089	Assumed to be emitted to air (solvent extraction)
Output	Deionized wash water	6.0	6.0	6.0	Assumed to be liquid aqueous waste. (Solvent extraction)
Output	Sodium sulfate	0.59	0.23	1.0	Assumed to be liquid aqueous waste. (Solvent extraction)
Output	Ammonia gas	0.10	0.0025	0.19	Assumed to be an emission to air. (Crystallization)
Output	Gangue	0.71	0.36	1.5	Assumed to be solid waste. (Hydrometallurgy)
Main output	APT	1.0	1.0	1.0	(Crystallization)

Table S11. Pyrometallurgy. All values are in kg per kg of tungsten carbide (WC) powder unless otherwise noted. APT=ammonium paratungstate. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Main input	APT	1.3	1.3	1.3	(Calcination)
Input	Electricity	7.8	3.5	12	kWh/kg WC powder. (Pyrometallurgy)
Input	Hydrogen	0.034	0.031	0.037	(Hydrogen reduction)
Input	Carbon black	0.065	0.063	0.067	(Carburization)
Input	Hydrogen	0.015	0.0055	0.024	(Carburization)
Output	Ammonia gas	0.094	0.0024	0.19	Assumed to be an emission to air. (Calcination)
Output	Hydrogen	0.0033	0.00041	0.0063	Assumed to be an emission to air. (Hydrogen reduction and carburization)
Output	Carbon dioxide	0.013	0.0045	0.022	Assumed to be an emission to air. (Carburization)
Main output	WC powder	1.0	1.0	1.0	(Carburization)

Table S12. Powder metallurgy. All values are in kg per kg of tungsten carbide with cobalt (WC-Co) unless otherwise noted. APT=ammonium paratungstate. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment (process or phase)
Main input	WC powder	0.91	0.84	0.99	(Powder milling)
Input	Cobalt powder	0.11	0.16	0.063	(Powder milling)
Input	Organic solvent	0.059	0.059	0.059	Base case: 50% hexane, 50% heptane, LS: hexane and HS: heptane. (Powder milling)
Input	Paraffin wax	0.041	0.020	0.063	(Powder milling)
Input	Nitrogen	0.13	0.073	0.21	(Granulation and compaction)
Input	Electricity	11	2	20	kWh/kg WC-Co (powder metallurgy)
Output	Organic solvent	0.010	0.0099	0.010	Assumed to be an emission to air. (Powder milling)
Output	Organic solvent	0.049	0.049	0.049	Assumed to be an emission to air. (Granulation and compaction)
Output	Un-granulated powder and paraffin	0.027	0	0.056	Assumed to be solid waste. (Granulation and compaction)
Output	Nitrogen	0.13	0.073	0.21	Assumed to be an emission to air. (Granulation and compaction)
Output	Paraffin	0.040	0.020	0.060	Assumed to be an emission to air. (Sintering)
Main output	Sintered WC-Co	1.0	1.0	1.0	(Sintering)

Table S13. Zinc recycling process. All values are in kg per kg of tungsten carbide (WC) and cobalt (Co) powder unless otherwise noted. WC-Co=tungsten carbide with cobalt. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

Input or output	Parameter	BC	LC	HC	Comment
Main input	WC-Co scrap	1.0	1.0	1.0	
Input	Zinc	0.0059	0.0051	0.0067	
Input	Electricity	2.8	1.5	4.0	kWh/kg WC and Co powder
Output	WC-Co loss	0.026	0.020	0.031	Assumed to be solid waste
Output	Zinc (g)	0.0059	0.0051	0.0067	Fugitive loss
Main output	WC and Co powder	1.0	1.0	1.0	
	WC powder	0.89	0.84	0.94	
	Co powder	0.11	0.16	0.060	

4. Life cycle inventory data results

Table S14. Life cycle inventory data for the zero recycling scenario. All values are in kg/ functional unit (f.u) unless otherwise noted. The functional unit is 1 kg WC-Co with a cobalt content of 6-16% and a WC grain size > 0.2 µm. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

MINING					
Input or output	**Parameter**	**BC**	**LC**	**HC**	**Comment**
Input	Anyl xanthate	0.0035	0.0030	0.0042	
Input	Diesel	20	7.9	47	MJ/f.u
Input	Electricity	2.1	2.6	0	kWh/f.u
Input	Frother	0.0038	0.0015	0.0065	
Input	Oleic acid	0.046	0.024	0.072	
Input	Pine oil	0.00071	0.00060	0.00084	
Input	Scheelite ore	180	110	310	
Input	Sodium carbonate	0.23	0.028	0.47	
Input	Sodium cyanide	0.018	0.0030	0.036	
Input	Sodium silicate	0.16	0.059	0.27	
Input	Sodium sulfide	0.088	0.075	0.10	
Input	Tannin	0.026	0.0030	0.054	
Input	Water	190	130	310	
Input	Wolframite ore	60	38	100	
Output	Carbon dioxide	0.13	0.068	0.21	Emitted to air
Output	Separated material	240	150	410	Tailings, landfilled. Base case: Half non-sulfidic and half sulfidic. LS: non-sulfidic. HS: sulfidic
Output	Separated flotation reagents	0.52	0.17	0.95	Landfilled with tailings.
TRANSPORT					
Input	Transport by lorry	7.7	7.0	9.1	ton·km/f.u
HYDROMETALLURGY					
Input	Alamine 336	0.12	0.11	0.13	
Input	Aluminum sulfate	0.044	0.041	0.048	
Input	Ammonia	0.22	0.015	0.45	
Input	Decanol	0.13	0.12	0.14	
Input	Deionized wash water	7.3	6.7	7.9	
Input	Electricity	1.6	1.1	2.1	kWh/f.u
Input	Kerosene	1.4	1.3	1.6	
Input	Magnesium sulfate	0.016	0.015	0.017	
Input	Sodium carbonate	1.3	0.85	1.8	
Input	Sodium hydrosulfide	0.059	0	0.14	

Input	Sodium hydroxide	0.051	0.047	0.057	
Input	Sulfuric acid	0.62	0.13	1.6	
Input	Tungsten scrap	0	0	0	
Input	Water	21	20	23	
Output	Alamine 336	0.12	0.11	0.13	Liquid organic waste
Output	Ammonia gas	0.13	0.013	0.27	Emitted to air
Output	Carbon dioxide	0.38	0.21	0.58	Emitted to air
Output	Decanol	0.13	0.12	0.14	Liquid organic waste
Output	Deionized wash water	7.3	6.7	7.9	Liquid aqueous waste
Output	Gangue	1.1	0.89	1.3	Solid waste
Output	Hydrogen sulfide	0.0040	0	0.0087	Emitted to air
Output	Kerosene	1.4	1.3	1.6	Liquid organic waste
Output	Molybdenum sulfide	0.022	0	0.049	Solid waste
Output	Sodium sulfate	0.97	0.25	2.4	Liquid aqueous waste
Output	Wash water	0.21	0	0.46	Liquid aqueous waste
PYROMETALLURGY					
Input	Carbon black	0.059	0.053	0.067	
Input	Electricity	7.1	2.9	12	kWh/f.u
Input	Hydrogen	0.044	0.031	0.060	
Output	Ammonia gas	0.086	0.0020	0.18	Emitted to air
Output	Carbon dioxide	0.012	0.0038	0.022	Emitted to air
Output	Hydrogen	0.0031	0.00035	0.0062	Emitted to air
POWDER METALLURGY					
Input	Cobalt powder	0.11	0.16	0.063	
Input	Electricity	11	2.0	20	kWh/f.u
Input	Nitrogen	0.13	0.073	0.21	
Input	Organic solvent	0.059	0.059	0.059	
Input	Paraffin wax	0.041	0.020	0.063	
Input	WC-Co scrap	0	0	0	
Input	Zinc	0	0	0	
Output	Nitrogen	0.13	0.073	0.21	Emitted to air
Output	Organic solvent	0.059	0.059	0.059	Emitted to air
Output	Paraffin	0.040	0.020	0.060	Emitted to air
Output	Sintered WC-Co	1.0	1.0	1.0	f.u
Output	Un-granulated powder	0.027	0	0.056	Solid waste
Output	WC-Co loss	0	0	0	Solid waste
Output	Zinc	0	0	0	Emitted to air

Table S15. Life cycle inventory data for the complete recycling scenario. All values are in kg/ functional unit (f.u) unless otherwise noted. The functional unit is 1 kg WC-Co with a cobalt content of 6-16% and a WC grain size > 0.2 µm. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

MINING					
Input or output	**Parameter**	**BC**	**LC**	**HC**	**Comment**
Input	Anyl xanthate	0	0	0	
Input	Diesel	0	0	0	MJ/f.u
Input	Electricity	0	0	0	kWh/f.u
Input	Frother	0	0	0	
Input	Oleic acid	0	0	0	
Input	Pine oil	0	0	0	
Input	Scheelite ore	0	0	0	
Input	Sodium carbonate	0	0	0	
Input	Sodium cyanide	0	0	0	
Input	Sodium silicate	0	0	0	
Input	Sodium sulfide	0	0	0	
Input	Tannin	0	0	0	
Input	Water	0	0	0	
Input	Wolframite ore	0	0	0	
Output	Carbon dioxide	0	0	0	Emitted to air
Output	Separated material	0	0	0	Tailings, landfilled. Base case: Half non-sulfidic and half sulfidic. LS: non-sulfidic. HS: sulfidic
Output	Separated flotation reagents	0	0	0	Landfilled with tailings.
TRANSPORT					
Input	Transport by lorry	0	0	0	ton·km/f.u
HYDROMETALLURGY					
Input	Alamine 336	0.061	0.058	0.065	
Input	Aluminum sulfate	0.022	0.021	0.023	
Input	Ammonia	0.11	0.0075	0.22	
Input	Decanol	0.062	0.058	0.065	
Input	Deionized wash water	3.6	3.4	3.8	
Input	Electricity	3.7	1.4	6.5	kWh/f.u
Input	Kerosene	0.72	0.67	0.76	
Input	Magnesium sulfate	0.0078	0.0073	0.0082	
Input	Sodium carbonate	0	0	0	
Input	Sodium hydrosulfide	0.026	0	0.11	
Input	Sodium hydroxide	0.43	0.38	0.48	
Input	Sulfuric acid	0.23	0.064	0.47	

Input	Tungsten scrap	0.66	0.42	1.2	
Input	Water	6.4	5.9	7.0	
Output	Alamine 336	0.061	0.058	0.065	Liquid organic waste
Output	Ammonia gas	0.065	0.0064	0.13	Emitted to air
Output	Carbon dioxide	0	0	0	Emitted to air
Output	Decanol	0.062	0.058	0.065	Liquid organic waste
Output	Deionized wash water	3.6	3.4	3.8	Liquid aqueous waste
Output	Gangue	0.43	0.20	1.0	Solid waste
Output	Hydrogen sulfide	0.0018	0	0.0066	Emitted to air
Output	Kerosene	0.72	0.67	0.76	Liquid organic waste
Output	Molybdenum sulfide	0.010	0	0.037	Solid waste
Output	Sodium sulfate	0.38	0.13	0.72	Liquid aqueous waste
Output	Wash water	0.092	0	0.35	Liquid aqueous waste
PYROMETALLURGY					
Input	Carbon black	0.029	0.027	0.032	
Input	Electricity	3.5	1.5	5.7	kWh/f.u
Input	Hydrogen	0.022	0.015	0.029	
Output	Ammonia gas	0.042	0.0010	0.088	Emitted to air
Output	Carbon dioxide	0.0061	0.0019	0.011	Emitted to air
Output	Hydrogen	0.0015	0.00017	0.0030	Emitted to air
POWDER METALLURGY					
Input	Cobalt powder	0.056	0.081	0.030	
Input	Electricity	12	2.7	22	kWh/f.u
Input	Nitrogen	0.13	0.073	0.21	
Input	Organic solvent	0.059	0.059	0.059	
Input	Paraffin wax	0.041	0.020	0.063	
Input	WC-Co scrap	0.53	0.51	0.56	
Input	Zinc	0.0031	0.0025	0.0037	
Output	Nitrogen	0.13	0.073	0.21	Emitted to air
Output	Organic solvent	0.059	0.059	0.059	Emitted to air
Output	Paraffin	0.040	0.020	0.060	Emitted to air
Output	Sintered WC-Co	1.0	1.0	1.0	f.u
Output	Un-granulated powder	0.027	0	0.056	Solid waste
Output	WC-Co loss	0.013	0.010	0.017	Solid waste
Output	Zinc	0.0031	0.0025	0.0037	Emitted to air

Table S16. Life cycle inventory data for the scheelite ore scenario. All values are in kg/functional unit (f.u) unless otherwise noted. The functional unit is 1 kg WC-Co with a cobalt content of 6-16% and a WC grain size > 0.2 µm. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

MINING					
Input or output	**Parameter**	**BC**	**LC**	**HC**	**Comment**
Input	Anyl xanthate	0.0037	0.0033	0.0042	
Input	Diesel	16	6.5	36	MJ/f.u
Input	Electricity	1.6	2.1	0	kWh/f.u
Input	Frother	0.0040	0.0016	0.0065	
Input	Oleic acid	0.048	0.026	0.073	
Input	Pine oil	0.00074	0.00065	0.00084	
Input	Scheelite ore	190	120	310	
Input	Sodium carbonate	0.24	0.031	0.47	
Input	Sodium cyanide	0.019	0.0032	0.036	
Input	Sodium silicate	0.16	0.065	0.27	
Input	Sodium sulfide	0.093	0.082	0.11	
Input	Tannin	0.028	0.0032	0.055	
Input	Water	180	130	270	
Input	Wolframite ore	0	0	0	
Output	Carbon dioxide	0.14	0.074	0.21	Emitted to air
Output	Separated material	190	120	310	Tailings, landfilled. Base case: Half non-sulfidic and half sulfidic. LS: non-sulfidic. HS: sulfidic
Output	Separated flotation reagents	0.55	0.19	0.95	Landfilled with tailings.
TRANSPORT					
Input	Transport by lorry	5.9	5.5	6.2	ton·km/f.u
HYDROMETALLURGY					
Input	Alamine 336	0.11	0.10	0.12	
Input	Aluminum sulfate	0.039	0.037	0.042	
Input	Ammonia	0.19	0.013	0.39	
Input	Decanol	0.11	0.10	0.12	
Input	Deionized wash water	6.5	6.1	6.8	
Input	Electricity	2.0	1.2	3.2	kWh/f.u
Input	Kerosene	1.3	1.2	1.4	
Input	Magnesium sulfate	0.014	0.013	0.015	
Input	Sodium carbonate	1.4	0.92	1.8	
Input	Sodium hydrosulfide	0.069	0	0.18	
Input	Sodium hydroxide	0.09	0.073	0.12	
Input	Sulfuric acid	0.67	0.12	1.7	

Input	Tungsten scrap	0.14	0.080	0.32	
Input	Water	20	19	21	
Output	Alamine 336	0.11	0.10	0.12	Liquid organic waste
Output	Ammonia gas	0.12	0.012	0.23	Emitted to air
Output	Carbon dioxide	0.40	0.23	0.58	Emitted to air
Output	Decanol	0.11	0.10	0.12	Liquid organic waste
Output	Deionized wash water	6.5	6.1	6.8	Liquid aqueous waste
Output	Gangue	1.1	0.87	1.2	Solid waste
Output	Hydrogen sulfide	0.0047	0	0.011	Emitted to air
Output	Kerosene	1.3	1.2	1.4	Liquid organic waste
Output	Molybdenum sulfide	0.026	0	0.062	Solid waste
Output	Sodium sulfate	1.03	0.23	2.5	Liquid aqueous waste
Output	Wash water	0.25	0	0.58	Liquid aqueous waste
PYROMETALLURGY					
Input	Carbon black	0.053	0.048	0.058	
Input	Electricity	6.3	2.7	10	kWh/f.u
Input	Hydrogen	0.039	0.028	0.052	
Output	Ammonia gas	0.076	0.0018	0.16	Emitted to air
Output	Carbon dioxide	0.011	0.0034	0.019	Emitted to air
Output	Hydrogen	0.0027	0.00031	0.0054	Emitted to air
POWDER METALLURGY					
Input	Cobalt powder	0.10	0.14	0.055	
Input	Electricity	11	2.1	21	kWh/f.u
Input	Nitrogen	0.13	0.073	0.21	
Input	Organic solvent	0.059	0.059	0.059	
Input	Paraffin wax	0.041	0.020	0.063	
Input	WC-Co scrap	0.12	0.10	0.14	
Input	Zinc	0.00067	0.00048	0.00095	
Output	Nitrogen	0.13	0.073	0.21	Emitted to air
Output	Organic solvent	0.059	0.059	0.059	Emitted to air
Output	Paraffin	0.040	0.020	0.060	Emitted to air
Output	Sintered WC-Co	1.0	1.0	1.0	f.u
Output	Un-granulated powder	0.027	0	0.056	Solid waste
Output	WC-Co loss	0.0029	0.0019	0.0043	Solid waste
Output	Zinc	0.00067	0.00048	0.00095	Emitted to air

Table S17. Life cycle inventory data for the wolframite ore scenario. All values are in kg/ functional unit (f.u) unless otherwise noted. The functional unit is 1 kg WC-Co with a cobalt content of 6-16% and a WC grain size > 0.2 µm. BC=baseline case, LC=low environmental impact case and HC=high environmental impact case.

MINING					
Input or output	**Parameter**	**BC**	**LC**	**HC**	**Comment**
Input	Anyl xanthate	0	0	0	
Input	Diesel	15	6	34	MJ/f.u
Input	Electricity	1.6	2.1	0	kWh/f.u
Input	Frother	0	0	0	
Input	Oleic acid	0	0	0	
Input	Pine oil	0	0	0	
Input	Scheelite ore	0	0	0	
Input	Sodium carbonate	0	0	0	
Input	Sodium cyanide	0	0	0	
Input	Sodium silicate	0	0	0	
Input	Sodium sulfide	0	0	0	
Input	Tannin	0	0	0	
Input	Water	61	30	130	
Input	Wolframite ore	180	120	300	
Output	Carbon dioxide	0	0	0	Emitted to air
Output	Separated material	180	120	300	Tailings, landfilled. Base case: Half non-sulfidic and half sulfidic. LS: non-sulfidic. HS: sulfidic
Output	Separated flotation reagents	0	0	0	Landfilled with tailings.
TRANSPORT					
Input	Transport by lorry	6.6	6.1	8.6	ton·km/f.u
HYDROMETALLURGY					
Input	Alamine 336	0.11	0.10	0.12	
Input	Aluminum sulfate	0.040	0.037	0.042	
Input	Ammonia	0.19	0.013	0.39	
Input	Decanol	0.11	0.10	0.12	
Input	Deionized wash water	6.5	6.1	6.9	
Input	Electricity	2.0	1.2	3.2	kWh/f.u
Input	Kerosene	1.3	1.2	1.4	
Input	Magnesium sulfate	0.014	0.013	0.015	
Input	Sodium carbonate	0	0	0	
Input	Sodium hydrosulfide	0.00012	0	0.00035	
Input	Sodium hydroxide	0.25	0.22	0.28	
Input	Sulfuric acid	0.16	0.12	0.22	

Input	Tungsten scrap	0.14	0.078	0.31	
Input	Water	13	13	13	
Output	Alamine 336	0.11	0.10	0.12	Liquid organic waste
Output	Ammonia gas	0.12	0.012	0.23	Emitted to air
Output	Carbon dioxide	0	0	0	Emitted to air
Output	Decanol	0.11	0.10	0.12	Liquid organic waste
Output	Deionized wash water	6.5	6.1	6.9	Liquid aqueous waste
Output	Gangue	0.62	0.44	1.20	Solid waste
Output	Hydrogen sulfide	0.0000078	0	0.000021	Emitted to air
Output	Kerosene	1.3	1.2	1.4	Liquid organic waste
Output	Molybdenum sulfide	0.000044	0	0.00012	Solid waste
Output	Sodium sulfate	0.30	0.23	0.39	Liquid aqueous waste
Output	Wash water	0.00041	0	0.0011	Liquid aqueous waste
PYROMETALLURGY					
Input	Carbon black	0.053	0.048	0.058	
Input	Electricity	6.3	2.7	10	kWh/f.u
Input	Hydrogen	0.040	0.028	0.052	
Output	Ammonia gas	0.077	0.0018	0.16	Emitted to air
Output	Carbon dioxide	0.011	0.0034	0.019	Emitted to air
Output	Hydrogen	0.0027	0.00031	0.0054	Emitted to air
POWDER METALLURGY					
Input	Cobalt powder	0.10	0.15	0.055	
Input	Electricity	11	2.1	21	kWh/f.u
Input	Nitrogen	0.13	0.073	0.21	
Input	Organic solvent	0.059	0.059	0.059	
Input	Paraffin wax	0.041	0.020	0.063	
Input	WC-Co scrap	0.11	0.094	0.14	
Input	Zinc	0.00065	0.00047	0.00091	
Output	Nitrogen	0.13	0.073	0.21	Emitted to air
Output	Organic solvent	0.059	0.059	0.059	Emitted to air
Output	Paraffin	0.040	0.020	0.060	Emitted to air
Output	Sintered WC-Co	1.0	1.0	1.0	f.u
Output	Un-granulated powder	0.027	0	0.056	Solid waste
Output	WC-Co loss	0.0028	0.0019	0.0042	Solid waste
Output	Zinc	0.00065	0.00047	0.00091	Emitted to air

5. Life cycle impact assessment results

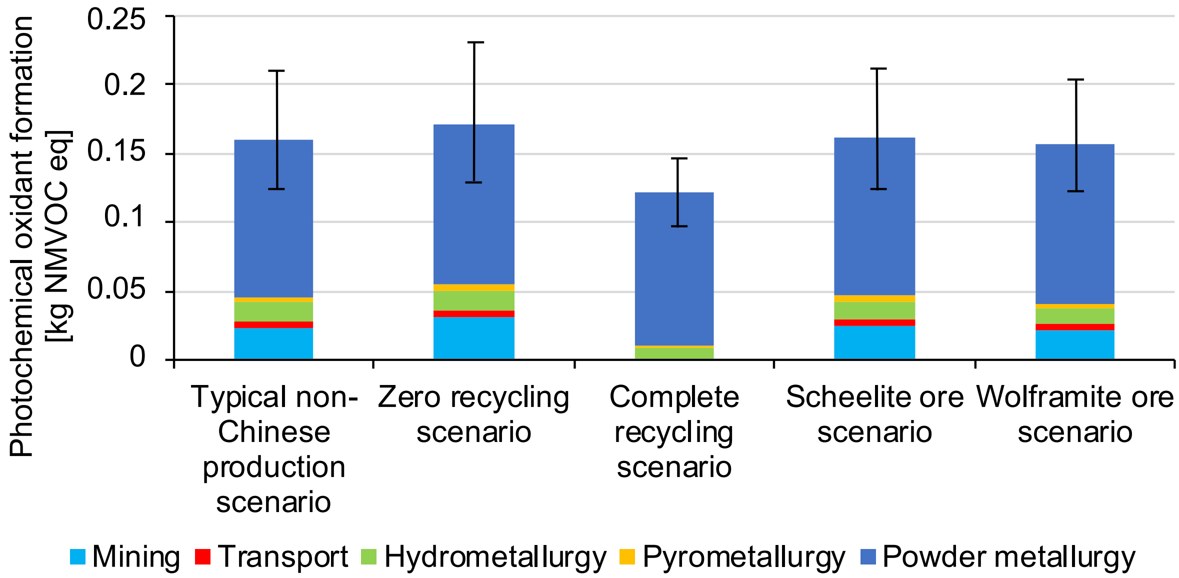

Figure S1. Photochemical oxidant formation results per kg WC-Co. Bars show the baseline case (BC) and ranges the low and high environmental impact scenarios (LC and HC, respectively).

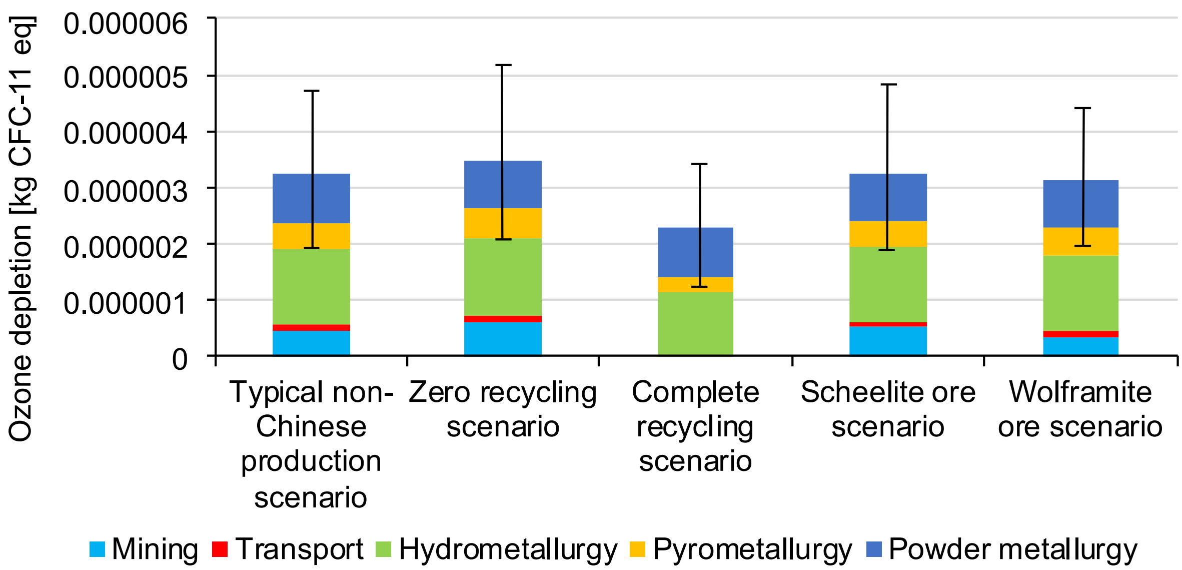

Figure S2. Ozone depletion results per kg WC-Co. Bars show the baseline case (BC) and ranges the low and high environmental impact scenarios (LC and HC, respectively).

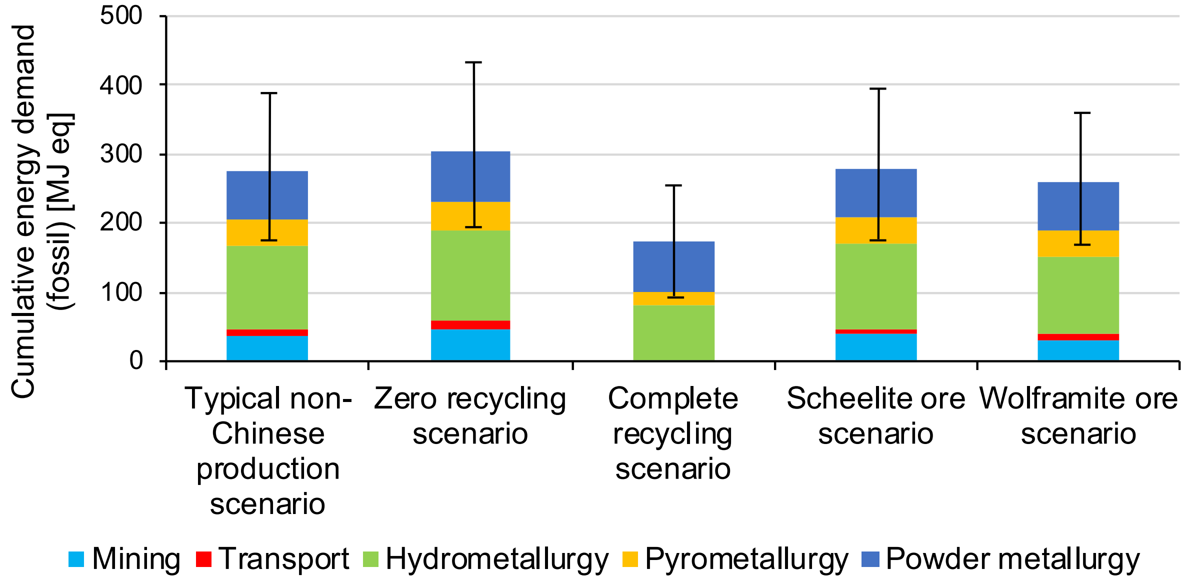

Figure S3. Cumulative energy demand (fossil) results per kg WC-Co. Bars show the baseline case (BC) and ranges the low and high environmental impact scenarios (LC and HC, respectively).

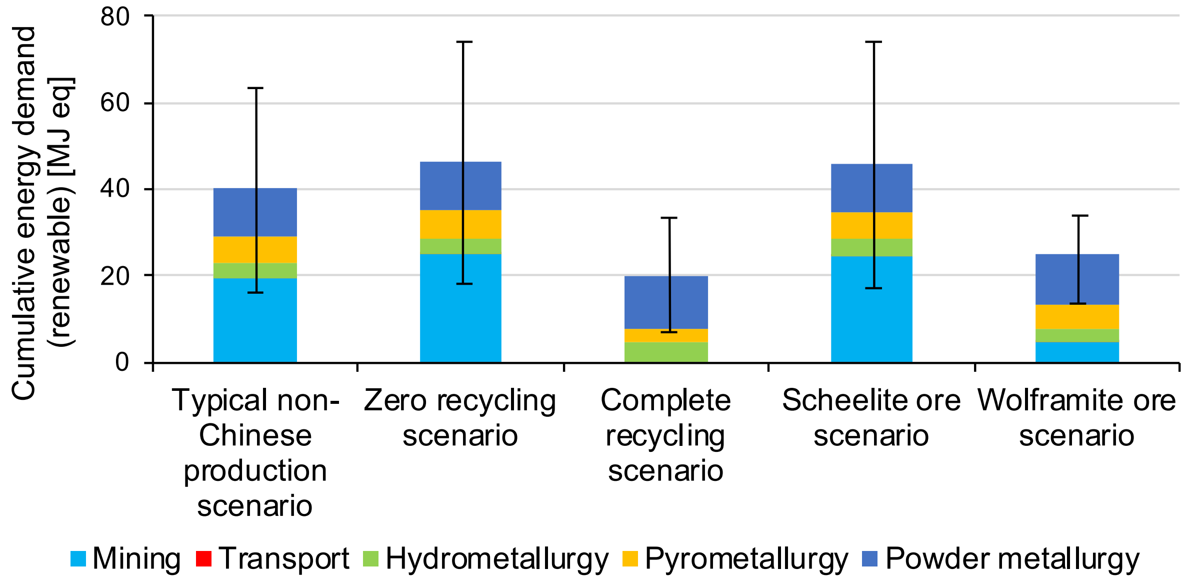

Figure S4. Cumulative energy demand (renewable) results per kg WC-Co. Bars show the baseline case (BC) and ranges the low and high environmental impact scenarios (LC and HC, respectively).

6. Comparison of Chinese and non-Chinese WC production

Table S18. Comparison of life cycle inventory results for the baseline case for the typical non-Chinese production in this study and Chinese production in the study by Ma et al. (2017) of 1 kg tungsten carbide (WC). Note that all parameters are given in kg/kg WC unless otherwise noted.

Input/ output	Parameter	Chinese WC production, (Ma et al., 2017)	Typical non-Chinese WC production (baseline case, this study)	Comment
Mining and transport (tungsten ore mining and tungsten concentrate production in Ma et al. (2017))				
Input	2# oil	0.0088	-	
Input	Anyl xanthate	-	0.0030	
Input	Coal oleic acid	0.053	-	
Input	Copper sulfate	0.032	-	
Input	Diesel	-	17	MJ/kg WC
Input	Electricity	30	1.8	kWh/kg WC
Input	Explosive	0.51	-	
Input	Frother	-	0.0032	
Input	Iron	0.15	-	
Input	Kerosene	0.053	-	
Input	Land occupation	0.090	-	m^2/kg WC
Input	Oleic acid	-	0.039	
Input	Pine oil	-	0.00060	
Input	Scheelite ore	-	154	
Input	Sodium carbonate	-	0.20	
Input	Sodium cyanide	-	0.015	
Input	Sodium fluosilicate	0.067	-	
Input	Sodium hydroxide	0.053	-	
Input	Sodium silicate	0.00015	0.13	
Input	Sodium sulfide	-	0.076	
Input	Steel	0.88	-	
Input	Tannin	-	0.022	
Input	Transport by lorry	-	6.6	ton·km/f.u
Input	Water	146	163	
Input	Wolframite ore	-	52	
Input	Wood	0.0018	-	m^3/kg WC
Input	Xanthate	0.029	-	
Output	Barren rock reuse	78	-	
Output	Carbon dioxide	-	0.11	Emitted to air
Output	Gangue storage	360	-	
Output	Separated material	-	210	Tailings, landfilled. Base case: Half non-sulfidic and half sulfidic

Input/ output	Parameter	Chinese WC production, (Ma et al., 2017)	Typical non-Chinese WC production (baseline case, this study)	Comment
Output	Separated flotation reagents	-	0.45	Landfilled with tailings
Output	Sewage sludge to landfill	88	-	
Output	Sewage water treatment	0.096	-	m^3/kg WC
Output	Waste iron	64	-	
Output	Wastewater to river	250	-	
Output	Wood waste	46	-	
Hydrometallurgy (APT production in Ma et al. (2017))				
Input	Alamine 336	-	0.12	
Input	Aluminum sulfate	-	0.043	
Input	Ammonia	-	0.21	
Input	Ammonium sulphide (17%)	0.060	-	
Input	Ammonium chloride	0.41	-	
Input	Calcium carbonate	0.0012	-	
Input	Coal	1.3	-	
Input	Copper sulfate	0.023	-	
Input	Decanol	-	0.12	
Input	Electricity	0.74	2.2	kWh/kg WC
Input	Hydrochloric acid (37%)	0.015	-	
Input	Hydrogen peroxide	0.0012	-	
Input	Kerosene	-	1.4	
Input	Land occupation	0.00022	-	m^2/kg WC
Input	Liquid ammonia	0.073	-	
Input	Magnesium sulfate	-	0.015	
Input	Sodium carbonate	-	1.1	
Input	Sodium hydrosulfide	-	0.056	
Input	Sodium hydroxide	0.61	0.15	
Input	Sulfuric acid	0.062	0.59	
Input	Tungsten scrap	-	0.16	
Input	Water	120	27	Water and deionized water
Output	Alamine 336	-	0.12	Liquid organic waste
Output	Ammonia gas	-	0.13	Emitted to air
Output	Carbon dioxide	-	0.32	Emitted to air
Output	Decanol	-	0.12	Liquid organic waste
Output	Deionized wash water	-	7.1	Liquid aqueous waste

Input/ output	Parameter	Chinese WC production, (Ma et al., 2017)	Typical non-Chinese WC production (baseline case, this study)	Comment
Output	Gangue	-	1.1	Solid waste
Output	Hydrogen sulfide	-	0.0038	Emitted to air
Output	Kerosene	-	1.4	Liquid organic waste
Output	Molybdenum sulfide	-	0.021	Solid waste
Output	Sodium sulfate	-	0.92	Liquid aqueous waste
Output	Wash water	-	0.20	Liquid aqueous waste
Pyrometallurgy and Zinc recycling (WC powder production in Ma et al. (2017))				
Input	Carbon black	0.070	0.058	
Input	Compressed air	0.11	-	m^3/kg WC
Input	Electricity	16	7.2	kWh/kg WC
Input	Hydrogen	-	0.043	
Input	Land occupation	0.00073	-	m^2/kg WC
Input	Nitrogen	0.044	-	m^3/kg WC
Input	Water	1.3	-	
Input	WC-Co scrap	-	0.13	
Input	Zinc	-	0.00073	
Output	Ammonia gas	-	0.084	Emitted to air
Output	Carbon dioxide	-	0.012	Emitted to air
Output	Hazardous waste	0.81	-	This output is for both APT and WC powder production
Output	Hydrogen	-	0.0030	Emitted to air
Output	Industrial solid waste	0.73	-	This output is for both APT and WC powder production
Output	Municipal solid waste to landfill	0.028	-	This output is for both APT and WC powder production
Output	Wastewater treatment	0.096	-	m^3/kg WC. Note that this output is for both APT and WC powder production
Output	WC-Co loss	-	0.0032	Solid waste
Output	Zinc	-	0.00073	Emitted to air

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