

Supplementary Material

S.1. Log-Logistic Cumulative Cost-Extraction Distributions

Table S1. Data used for deriving the cumulative cost-tonnage distributions of the period 2000 to 2012 or 2013 depending on the metal [1].

Metal	Number of Mines	Production Coverage	Total Metal Extracted in Data Sample Used $A_{x,sample}$ (kg _x)
Copper	199	83% of Western worlda	1.67×10^{11}
Iron	171	85% of Western worlda	1.03×10^{13}
Lead	82	86% of Western worlda	2.45×10^{10}
Manganese	9	90% of Western worlda	9.23×10^{10}
Molybdenum	32	89% of Western worlda	1.65×10^9
Nickel	81	85% of Western worlda	1.53×10^{10}
Palladium	26	90% of total world	2.23×10^6
Platinum	26	90% of total world	2.08×10^6
Rhodium	25	90% of total world	2.59×10^5
Silver	187	72% of Western worlda	1.66×10^8
Uranium	25	67% of total world	3.83×10^8
Zinc	114	83% of Western worlda	7.11×10^{10}
Platinum-group metals	39	90% of total world	4.63×10^6

Note: The Western world is defined as including all cultures that are directly derived from and influenced by European cultures, *i.e.*, Europe, the Americas, South Africa, and Oceania (Australia and New Zealand).

Table S2. Future production data used for the calculation of maximum metal extracted (MME), namely reserves and ultimate recoverable resource [2–6].

Metal	Reserves R_R (kg _x)	Ultimate Recoverable Resource R_{URR} (kg _x)
Copper	6.90×10^{11}	4.63×10^{12}
Iron	8.10×10^{13}	6.46×10^{15}
Lead	8.90×10^{10}	2.81×10^{12}
Manganese	5.70×10^{11}	1.27×10^{14}
Molybdenum	1.10×10^{10}	1.82×10^{11}
Nickel	7.40×10^{10}	7.76×10^{12}
Palladium	2.31×10^7	7.74×10^7
Platinum	3.12×10^7	1.05×10^8
Rhodium	3.30×10^6	1.11×10^7
Silver	5.20×10^8	2.00×10^{10}
Uranium	2.52×10^9	4.30×10^{11}
Zinc	2.50×10^{11}	1.11×10^{13}
Platinum-group metals	6.60×10^7	2.21×10^8

Table S3. Parameters derived for the log-logistic cumulative cost-tonnage distribution.

Metal	Log-Logistic Distribution		R ²
	scale α (95% CI)	shape β (95% CI)	
Copper	−0.88 (−0.89 to −0.88)	0.13 (0.13 to 0.13)	0.96
Iron	3.44 (3.43 to 3.44)	0.19 (0.18 to 0.19)	0.97
Lead	0.36 (0.35 to 0.37)	0.13 (0.13 to 0.14)	0.97
Manganese	−2.73 (−2.78 to −2.69)	0.06 (0.04 to 0.08)	0.81
Molybdenum	−2.58 (−2.60 to −2.57)	0.10 (0.09 to 0.10)	0.96
Nickel	−2.32 (−2.33 to −2.31)	0.15 (0.14 to 0.15)	0.91
Palladium	−8.92 (−8.96 to −8.88)	0.12 (0.10 to 0.14)	0.77
Platinum	−9.91 (−9.23 to −9.89)	0.15 (0.14 to 0.16)	0.95
Rhodium	−10.6 (−10.7 to −10.6)	0.15 (0.14 to 0.17)	0.82
Silver	−5.41 (−5.42 to −5.41)	0.19 (0.19 to 0.19)	0.97
Uranium	−4.00 (−4.02 to −3.98)	0.14 (0.13 to 0.15)	0.92
Zinc	−1.48 (−1.56 to −1.40)	0.54 (0.53 to 0.55)	0.97
Platinum-group metals	−9.57 (−9.61 to −9.53)	0.17 (0.16 to 0.18)	0.86

Notes: CI = confidence interval; R² = coefficient of determination.

S.2. Characterization Factors

Table S4. Sensitivity analysis for reserve estimates in deriving CFs with reserves and ultimate recoverable resource.

Mineral	Surplus Cost Potential (USD ₂₀₁₃ /kg _x)		Factor Difference between SCP _R and SCP _{URR}
	Reserves	Ultimate Recoverable Resources	
Copper	5.21×10^{-1}	7.44×10^{-1}	1.4
Iron	1.15×10^{-2}	2.20×10^{-2}	1.9
Lead	1.44×10^{-1}	2.40×10^{-1}	1.7
Manganese	1.39×10^0	4.42×10^0	3.2
Molybdenum	2.15×10^0	3.97×10^0	1.8
Nickel	2.54×10^0	5.62×10^0	2.2
Palladium	1.92×10^3	2.48×10^3	1.3
Platinum	6.30×10^3	7.99×10^3	1.3
Rhodium	1.35×10^4	1.71×10^4	1.3
Silver	7.31×10^1	1.14×10^2	1.6
Uranium	1.21×10^1	2.90×10^1	2.4
Zinc	9.04×10^0	6.69×10^0	0.7
Platinum-group metals	5.35×10^3	6.65×10^3	1.2

S.3. Comparison with Other Monetary Results

The weighted average mining and milling costs per kilogram of metal extracted were calculated based on the metal production and the costs per mine in 2013 as reported in the World Mine Cost Data Exchange [1]. There is about six orders of magnitude difference for the average mining and milling costs between the metals under study, from around \$0.05 USD per kilogram of iron extracted to about \$48,000 USD per kilogram of rhodium (see Table S5).

Table S5. Current operating costs [1], characterization factors derived in the ReCiPe method with 3% discounting [7], and characterization factors derived in the EPS method [8].

Metal	Current Operating Costs (USD ₂₀₁₃ /kg _x)	CF in the ReCiPe Method (USD ₂₀₁₃ /kg _x)	CF in the EPS Method (ELU/kg _x)
Copper	3.72	3.06	208
Iron	0.05	0.07	0.96
Lead	1.47	0.13	175
Manganese	22.1	5.48	5.64
Molybdenum	12.7	14.9	2,120
Nickel	14.4	0.90	160
Palladium	13,281	273	7,430,000
Platinum	38,794	11,652	7,430,000
Rhodium	47,911	1,455	49,500,000
Silver	424	20.5	54,000
Uranium	62.1	8.77	1,190
Zinc	5.94	0.16	57.1

References

1. World Mine Cost Data Exchange. Cost Curves. Available online: www.minecost.com/curves.htm (accessed on 2 July 2014).
2. U.S. Geological Survey. *Mineral Commodity Summaries 2014*; U.S. Geological Survey: Reston, VA, USA, 2014. Available online: <http://minerals.usgs.gov/minerals/pubs/mcs/2014/mcs2014.pdf> (accessed 3 October 2014).
3. Hall, S.; Coleman, M. *Critical Analysis of World Uranium Resources*. U.S. Scientific Investigations Report 2012–5239; U.S. Geological Survey: Reston, VA, USA, 2012.
4. Pincock, Allen and Holt The Processing of Platinum Group Metals (PGM)—Part 1. Pincock Perspectives 89, March 2008. Available online: www.pincock.com/perspectives/Issue89-PGM-Processing-Part1.pdf (accessed on 5 November 2012).
5. Schneider, L.; Berger, M.; Finkbeiner, M. Abiotic resource depletion in LCA—background and update of the anthropogenic stock extended abiotic depletion potential (AADP) model. *Int. J. Life Cycle Assess.* **2015**, *20*, 709–721.
6. UNEP. *Estimating long-run geological stocks of metals*; UNEP International Panel on Sustainable Resource Management, Working Group on Geological Stocks of Metal: Paris, France, 2011. Available online: <http://www.unep.org/resourcepanel/Portals/24102/PDFs/GeolResourcesWorkingpaperfinal040711.pdf> (accessed on 24 December 2015).
7. Goedkoop, M.; de Schryver, A. Mineral Resource Depletion. In *ReCiPe 2008: A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. Report I: Characterisation Factors*, 1st ed.; Goedkoop, M., Heijungs, R., Huijbregts, M.A.J., de Schryver, A., Struijs, J., van Zelm, R., Eds.; Ministerie van Volkhuysvesting, Ruimtelijke Ordening en Milieubeheer: Den Haag, the Netherlands, 2009; pp. 108–117.
8. Steen, B. A systematic approach to environmental priority strategies in product development (EPS). Version 2000—Models and Data of the Default Method; Chalmers University of Technology: Gothenburg, Sweden, 1999.



© 2016 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons by Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).