Electronic Supplementary Material (ESI) for Environmental Science: Nano.

Electronic Supplementary Information for:

Engineered nanomaterials in the context of global element cycles

Nina Z. Janković[1,3] and Desirée L. Plata*[1,2,3]

[1]Department of Chemical and Environmental Engineering, Yale University, New Haven CT, 06511

[2]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02142

[3]Center for Green Chemistry and Green Engineering, Yale University, 225 Prospect Street, New Haven, CT, 06520

*corresponding author: dplata@mit.edu

Global Material Efficiencies

Global nanomaterial production volumes were obtained from *The Global Nanotechnology and Nanomaterials Market Opportunity Report* [1]. The anthropogenic flows considered herein are those from mining, spanning the entire life cycle of a primary material from raw material extraction to the end-of-life phase. World mine, smelter, and/or refinery production volumes for 2014 were obtained from the U.S. Geological Survey (USGS) Minerals Yearbook, USGS Commodity Summaries, and the International Nickel Study Group (INSG) –see tables below. It should be noted that USGS minerals reports often withhold U.S. production volumes to avoid disclosing company proprietary data.

Global material efficiencies (Figure 3) across a single life cycle (i.e., rates of material flow through the life cycle within a given year) were calculated from global anthropogenic element cycles available in the literature with the exception of cobalt, copper, and nickel, where production losses were partially calculated from values reported by the USGS Minerals Yearbooks, USGS Commodity Summaries, and the INSG (refer to Table S1). Sufficient data were available for the 2014 cobalt, copper, and nickel production volumes to supplement cycling efficiencies calculated from the literature (i.e. cycles for years preceding 2014). Therefore, production efficiencies were calculated *ab initio* when possible. Primary material flows were decoupled from secondary flows, within the limit of available data, using cycling rates calculated from the literature. Efficiencies were calculated across one life cycle; therefore, stock accumulation was omitted and the entirety of materials mined were assumed to reach the end-of-life phase within the same year. The use phase and end-of-life cycling rates for copper were calculated from the International Copper Study Group (ICSG) 2013 cycle. Global material mass flows for 2014 were calculated (in Gg) from the associated material cycling rates (refer to Table S1).

Details pertaining to the nickel cycle

Nickel is extracted from two types of ores: sulfide ores and laterite ores. Sulfide ores deposits are mined underground and separated from gangue minerals through beneficiation of crushed ore, i.e. froth flotation and magnetic separation processes.

Subsequently, nickel concentrates are further purified through a leaching or smelting process. Smelting yields a nickel-iron sulfide, known as nickel matte, which can further be processed and refined into nickel metal, ferronickel, nickel oxide sinter, and nickel chemicals. Lateritic ores are found near the surface and are mined in earth-moving operations. Laterite ores are typically low-grade deposits, which are “difficult to concentrate by common ore beneficiation processes”[2]. Thus, large amounts of laterite ore must be smelted to concentrate the contained nickel. Laterite ore processing includes a variety of hydrometallurgical techniques (i.e. leaching) followed by solvent extraction-electrowinning (SXEW). Both sulfide and laterite ores are processed to nickel matte and refined to the various nickel products (listed above), albeit through diverse metallurgical routes. From the 2005 Ni cycle, the largest losses of nickel to tailings are from crushing/milling sulfide ore.

Nickel production losses (i.e. tailings and slag) were 18% of ore production (i.e. extracted metal) in 2005[3] and 29% in 2014 (Table S1). The same loss rate to tailings in 2005, calculated from Reck[3], was applied to the 2014 cycle in the absence of sufficient 2014 data. However, sufficient data was available to calculate losses to slag, leaching, and refining. The production efficiency of nickel fell 11% between 2005 and 2014 (Table S1). This shift in production efficiency can be reconciled by (1) an increase in lower grade ore mining, (2) a redundancy in reported mine and plant production efficiency, or (3) a discrepancy in data sources used. To interrogate (1), the reported mine production figures must be dissected. The USGS reports mine production as laterite ore, concentrates (assumed to originate from sulfide ore), ore and ore milled (assumed to originate from sulfide ore), ferronickel, nickel sulfate, and unspecified/undifferentiated. The latest USGS data available with the above breakdown for mine production is 2013. The USGS world mine production figure for 2014 used here is reported only as a total sum of world mine production. In 2005 concentrates dominated the world mine production value, accounting for 35% of the total; conversely in 2013 laterite ore dominated mine production, accounting for 52% of the total. Laterite ore mine production dramatically increased after 2011 (likely to accommodate the increase in China’s nickel pig iron production). The increase in mining lower grade ores may account for the decrease in production rate of refined nickel products. An increase in laterite ore mining implies an increase in losses to leaching and slag, not to tailings. Thus, the 11% difference is likely an overestimate, assuming nickel losses to tailings were predominantly from milling of sulfide ore (similarly to 2005), whose production has remained stable since 2005. A redundancy in data reported for mine production and refinery production (nickel products) could not exclusively account for the totality of the 11% discrepancy, as ferronickel and nickel sulfide make up a small portion of the reported mine production.

Finally, the source data for 2005 nickel production was the INSG, which reports mine production as nickel contained in laterite ore mined and nickel contained in sulfide ore concentrates. Additionally, losses to tailings and slag were calculated from company data for 2005. While the data sources for mine production differ from 2005 and 2014, resolving an 11% divergence in production efficiency based on a discrepancy in reporting alone is unlikely. Nevertheless, a combination of any of the factors described above could certainly account for the observed divergence.

		WORLD PRODUCTION				Enters Fabrication, Manufacturing, & Use			F&M	USE			Enters Waste Management		
Element	**Cycle Year**	**Ore Production**	**Tailings**	**Mine Production**	**Slag, Leaching, Dross, By-products, Residues**	**Primary Smelter Production**	**Primary Refinery Production**	**Total Production Losses (b)**	**Fabrication & Manufacturing Losses (c)**	**Flow from use phase**	**In-use Dissipation (d)**	**In-use Dissipation Rate**	**Discards**	**Recycling**	**Non-functional Recycling**
Ag (Gg)	1997	20.2	4	16.2	1.4		14.8	5.4					14.02	7.95	
	(a)	100%	20%	80%	7%		73%	27%						42%	
	2014	33.4	6.62	***26.8***	2.32		24.5	8.94						13.9	
Al (Gg)	2009	37200	7400	29800	400	29700	29400	7800		19100	1200	6%	17900	9800	
	(a)	100%	20%	80%	1%	80%	79%	21%			5%			41%	
	2014	67590	13445	54145	727	***53963***	53418	14172			3356			27408	
Ce (Gg)	2007	42	8.4	33.6	3.3		30.3	11.7	4.4				21.6		
	(a)	100%	20%	80%	8%		72%	28%	10%						
	2014	63.6	12.7	***50.9***	5.00		45.9	17.7	6.66						
Co (Gg)	2005	126.7	63.35	63.35	9.272		54.078	72.622					40.523	9.009	3.643
	(a)	100%	50%	50%	7%		43%	57%						9%	4%
	2014	246	123	***123***	32		***91.3***	154						20.3	8.21
	(a)	100%	50%	50%	13%		37%	63%						8%	3%
Cu (Gg)	2013									12100	500	4%	11600	4050	
	(a)	100%					82%	18%			3%			27%	
Total	2014	22397		18509			18292	4105			756			6122	
	(a)	100%			15%		85%	15%							
Leaching, electrowon		4791			719		***4072***	719							
	(a)	100%	18%	82%	1%		81%	19%							
Concentrates, other		17606	3169	***14437***	218		***14220***	3387							
Fe (Gg)	2000	694000	92000	602000	28000		574000	120000		265000	8000	3%	351000	267000	
	(a)	100%	13%	87%	4%		83%	17%			2%			61%	
	2014	1645642	218154	***1427488***	66395		1361093	284549			41090			1004105	
Ni (Gg)	2005	1585	205	1380	85		1295	290					650	410	105
	(a)	100%	13%	87%	5%		82%	18%						52%	13%
	2014	2814	364	***2450***	456		***1994***	820						1258	322
	(a)	100%	13%	87%	16%		71%	29%						45%	11%
Zn (Gg)	2010	14000	1800	12200	760	11440		2560		8300	1100	13%	10100	4700	
	(a)	100%	13%	87%	5%	82%		18%			11%			33%	
	2014	15294	1966	***13327***	830	12497		2797			1656			5045	

Table S1. Bolded and italicized data are 2014 production values reported by USGS and/or INSG. These values provide a starting basis for calculation of all other 2014 global material efficiency values (i.e., data presented in Figure 3 and in the 2014 rows listed here), where that calculation relies on various element cycling rate data calculated from the listed references on an element-by-element basis.
(a) Global material efficiencies were calculated across a single life cycle of the particular element; primary materials were deconvoluted from secondary materials to the extent possible.
(b) Total losses during production are titled as "Tailings & Slag" in Figure 4.; this value includes all production losses (e.g. leaching, dross).
(c) Fabrication and manufacturing losses, originating from primary materials, were calculated for cerium, as there are no secondary cerium sources, i.e. the EOL-RR for Ce is zero. Fabrication and manufacturing losses for all other cycles are assumed to be zero.
(d) In-use dissipation is relevant to Al, Cu, Fe, and Zn cycles; these are flows from the use phase that do not enter waste management.
(e) Dissipation is the flow of waste from waste management that is informally discarded directly to the environment. This definition is specific to the Ag cycle.
(f) For the iron cycle, landfill flow includes end-of-life dispersion to the environment.

		WASTE MANAGEMENT					END-OF-LIFE RATES						
							Recycling Rate						
Element	Cycle Year	Dissipation (e)	Landfill (f)	Incineration	Other Repository	Processing or Separation Loss	End-of-life Recycling Rate (EOL-RR)	Non-functional Recycling Rate	Dissipation rate	Landfill Rate	Incineration Rate	Other Repository Rate	Processing or Separation Loss Rate
Ag (Gg)	1997	2.1	4				57%		15%	29%			
	(a)	11%	21%										
	2014	3.67	6.99										
Al (Gg)	2009			4700	3200	200	55%				26%	18%	1%
	(a)			19%	13%	1%							
	2014			13145	8950	559							
Ce (Gg)	2007		21.6							100%			
	(a)		62%										
	2014		39.2										
Co (Gg)	2005		27.871				22%	9%		69%			
	(a)		29%										
	2014		62.8										
	(a)		26%										
Cu (Gg)	2013		5700			1850	35%			49%			16%
	(a)		38%			12%							
Total	2014		8617			2797							
	(a)												
Leaching, electrowon													
	(a)												
Concentrates, other													
Fe (Gg)	2000		84000				76%			24%			
	(a)		19%										
	2014		315898										
Ni (Gg)	2005		135				63%	16%		21%			
	(a)		17%										
	2014		414										
	(a)		15%										
Zn (Gg)	2010		5400				47%			53%			
	(a)		38%										
	2014		5796										

Table S1 cont'd. Bolded and italicized data are 2014 production values reported by USGS and/or INSG. These values provide a starting basis for calculation of all other 2014 global material efficiency values (i.e., data presented in Figure 3 and in the 2014 rows listed here), where that calculation relies on various element cycling rate data calculated from the listed references on an element-by-element basis.

(a) Global material efficiencies were calculated across a single life cycle of the particular element; primary materials were deconvoluted from secondary materials to the extent possible.

(b) Total losses during production are titled as "Tailings & Slag" in Figure 4.; this value includes all production losses (e.g. leaching, dross).

(c) Fabrication and manufacturing losses, originating from primary materials, were calculated for cerium, as there are no secondary cerium sources, i.e. the EOL-RR for Ce is zero. Fabrication and manuf acturing losses for all other cycles are assumed to be zero.

(d) In-use dissipation is relevant to Al, Cu, Fe, and Zn cycles; these are flows from the use phase that do not enter waste management.

(e)Dissipation is the flow of waste from waste management that is informally discarded directly to the environment. This definition is specific to the Ag cycle.

(f) For the iron cycle, landfill flow includes end-of-life dispersion to the environment.

Element	Cycle Year	Additional Information	References
Ag (Gg)	2014	Assumed all slag and leachate originated from primary smelter/ refinery production. Data in mass of silver content.	Johnson et al., 2005[4] U.S. Geological Survey Minerals Yearbook 2014[5]
Al (Gg)	2014	Mine production is defined as the production of alumina from bauxite. Tailings include mining losses and red mud. Smelter production is defined as the production of molten Al from alumina. Refinery production is defined as the production of Al ingot. 2014 primary smelter production may include the mass of secondary aluminum ingot and alloying materials, see USGS Minerals Yearbook 2015. Data in mass of aluminum content.	Liu et al., 2012[6] U.S. Geological Survey Minerals Yearbook 2015[7]
Ce (Gg)	2014	Rare earth elements mine production is reported in rare earth oxide equivalents by the USGS, as the rare earths occur jointly in ore deposits. CeO_2 content of rare earth oxides assumed to be 50% [8, 9]. Smelting/ refining processes are defined generally as the separation of individual rare earths from rare earth concentrates. Data reported herein is converted to cerium content.	Du and Graedel, 2011[10] U.S. Geological Survey Minerals Yearbook 2014[11]
Co (Gg)	2014	Approximate cobalt primary refinery production; refer to USGS Minerals Yearbook 2014 for further details on mine production and refinery production data. Refer to Harper et al. for a detailed description on waste generation in the production stages. Data in mass of cobalt content.	Harper et al., 2012[12] U.S. Geological Survey Minerals Yearbook 2014[13]
Cu (Gg)	2014	Mine production total, Gg: 18477 — Refinery production total, primary, Gg: 18292 Concentrates, Gg: 14437 — Other, Gg: 14220 Leaching, electrowon, Gg: 4040 — Electrowon, Gg: 4072	U.S. Geological Survey Minerals Yearbook 2014[15]
		The difference in mine production and refinery production of electrowon Cu (produced by the SXEW (solvent extraction/ electrowinning-process)) is due to a discrepancy between Zambia's mine production (leaching, electrowon estimate) and refinery production (electrowon figure). Herein, the reported refinery electrowon Cu figure is used. Data in mass of copper content.	U.S. Geological Survey Minerals Yearbook 2014[15]
		Cu losses in the SXEW-process are assumed to be 15% of ore production. Cu losses in the production of concentrates using the pyrometallurgical process are assumed to be 18% of ore production. Note that typically the smelting process is ~97% efficient and the electrolytic refining process is ~99% efficient (these values were not applied here). Herein, the waste resulting from smelting and refining is calculated as the difference between mine production and primary refinery production. Refer to supplemental information of Glöser et al., 2013 for details on Cu production processes.	Glöser et al., 2013[14]
		Waste management and in-use dissipation rates extracted from International Copper Study Group figure: *Industry Global Flows of Copper (2013) and Derived Recycling Rates*.	International Copper Study Group, 2015[16]
Fe (Gg)	2014	Assumed all slag and by-products originated from primary smelter/ refinery production. Smelter and refinery production is not differentiated; the reported figure represents the flow relevant to fabrication and manufacturing life stages. Mine production represents the total usable ore produced. Data in mass of iron content.	Wang et al., 2007[17] U.S. Geological Survey Minerals Yearbook 2014-Advance Data Release[18]
Ni (Gg)	2014	Assumed all slag originated from primary smelter production. Smelting and refining processes are not differentiated. Relevant flow of extracted nickel into fabrication and manufacturing is considered. Data in mass of nickel content.	Reck and Graedel, 2012[3]
		2005 mine production composition, and associated losses to tailings, assumed to be representative for 2014, due to lack of detailed mine production data. Refer to 2005 nickel study[19]. A detailed discussion can be found above.	U.S. Geological Survey Mineral Commodity Summaries 2016[20]
		Primary nickel production defined as the flow nickel originating from mine production and purified through smelting and/ or refining processes.	International Nickel Study Group, World Nickel Statistics 2015[21]
Zn (Gg)	2014	Global anthropogenic Zn cycle base case considered. Assumed all slag originated from primary smelter production; smelter production consists of zinc slab, which flows to fabrication and manufacturing. Data in mass of zinc content.	Meylan and Reck, 2015[22] U.S. Geological Survey Minerals Yearbook 2014[23]

Table S1 cont'd. Bolded and italicized data are 2014 production values reported by USGS and/or INSG. These values provide a starting basis for calculation of all other 2014 global material efficiency values (i.e., data presented in Figure 3 and in the 2014 rows listed here), where that calculation relies on various element cycling rate data calculated from the listed references on an element-by-element basis.

(a) Global material efficiencies were calculated across a single life cycle of the particular element; primary materials were deconvoluted from secondary materials to the extent possible.

(b) Total losses during production are titled as "Tailings & Slag" in Figure 4.; this value includes all production losses (e.g. leaching, dross).

(c) Fabrication and manufacturing losses, originating from primary materials, were calculated for cerium, as there are no secondary cerium sources, i.e. the EOL-RR for Ce is zero. Fabrication and manufacturing losses for all other cycles are assumed to be zero.

(d) In-use dissipation is relevant to Al, Cu, Fe, and Zn cycles; these are flows from the use phase that do not enter waste management.

(e) Dissipation is the flow of waste from waste management that is informally discarded directly to the environment. This definition is specific to the Ag cycle.

(f) For the iron cycle, landfill flow includes end-of-life dispersion to the environment.

Glossary

Note that general definitions are given here, and we direct the readers to the primary literature sources for *scope and system boundaries.*

Anthropogenic element cycles account for the stocks and flows of materials mobilized through human activity across relevant reservoirs/compartments.

Dissipation: The non-recovered portion of discards lost to the environment. *In-use dissipation*: materials lost to the environment during the use phase. *Related:* Dispersion.

Dross: Solid impurities present in molten metals during smelting.

Fabrication and manufacturing losses: Wastes from fabrication of semi-fabricated products and final products that enter the use phase (e.g., industrial scrap).

Fabrication, manufacturing, and use phase: Fabrication of semi-products (e.g., sheets, rolls), followed by the manufacturing process to transform materials into final goods. The resultant mass fraction of material goods flows to the use phase.

Incineration: Portion of discards disposed via burning (may include waste-to-energy).

Landfill: The non-recovered portion of material that enters waste management and recycling is assumed to be landfilled or lost to the environment.

Leaching: The extraction of minerals from ore through dissolution in acidic solutions.

Mine production: Production of mineral concentrates and/ or usable ore through one or more beneficiation steps. Mine production is the difference between ore production and tailings.

Nano: Mass fraction of engineered nanomaterials.

Natural element cycles account for natural material stocks and flows, or biogeochemical pathways by which elements are transformed and moved, through relevant geological and biological reservoirs or environmental compartments.

Nonfunctional recycling: Recovered material for another use in which that particular element's properties are *not* required/utilized.

Ore production (i.e., extraction): Metal content of ore removed from the lithosphere.

Other repository: Unidentified portion of materials entering waste management and recycling, this compartment likely arises to balance masses at the end-of-life. See primary cycle source.

Primary refinery production: Refining can include a variety of metallurgical purification techniques, such as electrolysis. Refining is the final processing step in production of pure metal (or alloy), which enters the fabrication stage, where semi-fabricated products such as metal sheets, plates, and rolls are produced. Primary refinery production is the difference between ore production and the total production/ separations wastes (as wastes originate only from primary sources herein).

Primary smelter production: Production of elemental metal from mineral concentrates, through the reduction of metal oxides. Smelting utilizes heat and reducing agents to reduce the desired metal and extract it from concentrates. Primary smelter production is the difference between mine production and slag (as slag originates only from primary sources herein).

Processing loss: Loss of discards due to processing of waste at the end-of-life. *Related:* Separations loss.

Recycling: Recovered fraction of mass that enters waste management and recycling (i.e., discards). Refer to source cycle for more detail (e.g., obsolete scrap, industrial scrap). *Functional recycling:* Material is recycled for another use in which that particular element's properties are required/utilized.

Residues: General term for separations waste/by-products generated in metallurgical processing.

Slag: The by-product of smelting. Slags are separations waste generated in metal smelting.

Tailings: Uneconomic portion of materials found in ore deposits (gangue). Gangue is separated from the mineral of interest typically through a beneficiation process that includes the crushing or milling of ore, followed by a flotation process.

Element	ENM Production Volume 2014 (Gg)		Mine Production 2014 (Gg)	Nano-Fraction of Mine Production 2014 (%)	
	Low Estimate	High Estimate		Low Estimate	High Estimate
Ag	0.1	0.4	27	0.5	2
Au	0.001	0.003	3	0.04	0.1
Bi	0.03	0.05	11	0.3	0.5
Ce	0.7	1	51	1	2
Cu	0.2	0.5	18509	0.001	0.002
Fe[a]	0.006	0.03	1427488	4E-07	2E-06
Fe[b]	0.006	0.03	1427488	4E-07	2E-06
Ni	0.005	0.02	2450	2E-04	8E-04
Sb	0.009	0.02	158	0.006	0.01
Sn	0.09	0.2	286	0.03	0.06
Ti[c]	20	89	3620	0.5	2
Zr[d]	1	26	671	0.2	4
Al	3	5	54145	0.005	0.01
Co	0.004	0.006	123	0.003	0.005
Mg[e]	0.009	0.02	9390	1E-04	2E-04
Mg[f]	0.009	0.02	970	9E-04	2E-03
Mn	0.001	0.002	17800	8E-06	1E-05
Si[g]	86	654	8110	1	8
Si[h]	86	654	2600	3	25
Zn	5	26	13327	0.04	0.2

Table S2. All values are in metal content of the particular element; nanomaterial metal content is calculated based on assumed chemical formulas listed in Table S6. Iron composition of nanomaterial is calculated based on the assumption that the total composition of the reported production volume is (a) Fe_2O_3 or (b) Fe_3O_4. (c) Ti mine production is the combination of ilmenite and rutile. (d) ZrO_2 content of Zr mineral concentrates assumed to be ca. 63% (Table S7). (e) Total magnesium production is assumed to be the sum of magnesite mine production and Mg metal; a fraction of Mg metal is produced from magnesite; dolomite ore production not available. (f) Primary Mg metal production; Mg content of Mg metal assumed to be ca. 100%. (g) Estimated Si content of ferrosilicon and silicon metal production. (h) Si metal production; Si content of Si metal assumed to be ca. 100%.
Refer to Table S1 for further details on mine production of select elements.

We performed Web of Science Core Collection searches for the total number of publications on each nanomaterial (e.g., material name + nano) and the terms "EHS", "environmental health and safety", "toxicity", "environment", "LCA", or "green chemistry." We then illustrate that there is no correlation with study rate and production volumes, as an example that environmental research is seldom prioritized by market volume. Here, we are cautious to note that market volumes should not be the only prioritization criteria. Below we note details about the search criteria.

"TOPIC" searches title, abstract, author keywords, and Keywords Plus.
Timespan=All years.
Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI.

TOPIC: (zinc oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (gold) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (nickel) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (nanodiamond) AND TOPIC: (X)
TOPIC: (nanofiber) AND TOPIC: (X)
TOPIC: (nanoclay) AND TOPIC: (X)
TOPIC: (cobalt oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (titanium dioxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (silicon oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (manganese oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (silver) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (zirconium oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (cerium oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (fullerene) AND TOPIC: (X)
TOPIC: (iron oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (copper oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (bismuth oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (magnesium oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (antimony tin oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (aluminum oxide) AND TOPIC: (nano) AND TOPIC: (X)
TOPIC: (quantum dot) AND TOPIC: (X)
TOPIC: (dendrimers) AND TOPIC: (X)
TOPIC: (nanocellulose) AND TOPIC: (X)
TOPIC: (graphene) AND TOPIC: (X)
TOPIC: (carbon nanotube) AND TOPIC: (X)

X = toxicity, environment, EHS, environmental health and safety, LCA, or green chemistry

While the possible search queries are innumerable, we note that the specific subset of search queries performed here is meant to be representative (i.e., demonstrate a pattern, which we expect to remain similar even if alternative/ other queries are run). Quotation marks and spelling variations were **not** used in these searches (i.e., search *words* are exact). Please, refer to Web of Science search rules.

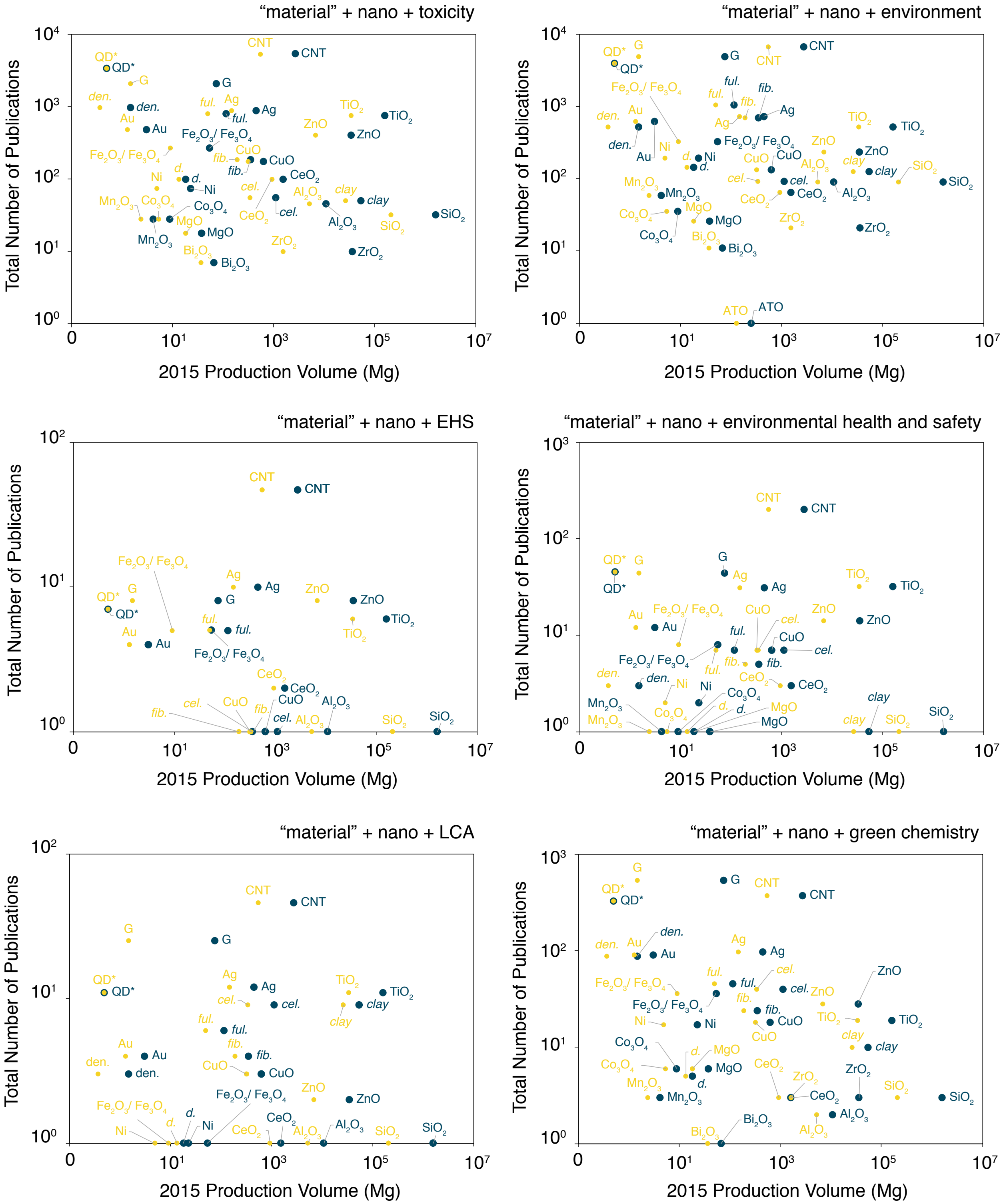

Figure S1. *nano*-EHS research focus versus ENM production volumes. Titles above each panel indicate words used in a Web of Science Core Collection search conducted on either June 03, 2019 (for LCA or green chemistry) or September 27, 2018 (for toxicity, environment, EHS, or environmental health and safety). Note that this is a log-log plot, and the use of log scale prevented plotting of zero values (i.e., publication search query equal to zero); these are plotted as n=1 publication. QDs (quantum dots; QDs*) had zero production mass in 2015, and so the 2016 production volume is displayed. Colors indicate upper (blue) and lower (yellow) range of production volume estimates.

Technology Readiness Level

ENM	Applied R&D	Demonstration	Commercial
Aluminum Oxide	Medical implants	Environmental adsorbents	Anti-wear coatings
	Environmental adsorbents	Conductive coatings	Nanofillers for polymer composites
		Filtration membranes	Catalysts supports
			Heat transfer fluids
			Conductive coatings
			Propellants
			Polishing additives
			Paint additives
			Filtration membranes
			Specialty fibers
			Lubricants
n =	**2**	**3**	**11**
Antimony Tin Oxide	Smart windows	Lubricant oil	Anti-static coatings
	Lubricant oil	Catalysts	
	Catalysts	Sensors (humidity, gas)	
	Sensors (humidity, gas)	LIB & SIB battery additives	
	LIB & SIB battery additives	EMI shielding coatings	
	EMI shielding coatings	Conductive coatings	
	IR attenuation films and coatings	Conductive composites	
		IR attenuation films and coatings	
n =	**7**	**8**	**1**
Bismuth Oxide	Anti-microbial coatings	Medical device coatings	Ceramics
	Battery additives (anode)	Medical imaging (contrast agents, nanoprobes and biolabels)	
	Radioprotective textiles	Thermoelectric devices	
	Sensors	Solid oxide fuel cells	
	Medical imaging (contrast agents, nanoprobes and biolabels)	RFI shielding	
	Thermoelectric devices		
	Solid oxide fuel cells		
	RFI shielding		
n =	**8**	**5**	**1**
Carbon Nanotubes	Catalysts	Acoustics	Anti-static composites & films for electrostatic painting and static dissipation
	Imaging probes and fluorescent labels	PEM fuel cells	Marine coatings
	Electrochemical and gas phase hydrogen storage	E-textiles	Battery additives
	Solar cells	Electrochemical and gas phase hydrogen storage	Data cables & power transmission lines

ENM	Applied R&D	Demonstration	Commercial
	Drug delivery	Solar cells	De-icing coatings
	Conductors & semiconductors in lighter and more efficient solar cells (flexible foils)	Drug delivery	Thermoset composites, thermoplastics, and rubber additives
	Antibacterials	Conductors & semiconductors in lighter and more efficient solar cells (flexible foils)	Fuel system components
	Biosensors	Biosensors	Conductive additive in composites & pastes
		Stretchable films for electronics	Electromagnetic Interference Shielding (EMI) composites & coatings
		Supercapacitor additives	Automotive polymer composites
		Chemical sensors	Sporting goods composites
		Field emission devices	Aerospace composites
		Memory devices	Filtration membranes
		Fire retardant materials	Microscopy (TEM grids, SPM tips, AFM tips)
		TCF additives	EMI, ESD and antistatic, shielding coatings & composites
			TCF additives
n =	**8**	**15**	**16**
Cellulose	Anti-static coatings	Cement additives	Cement additives
	E-textiles	Printing paper	Printing paper
	Drug delivery	Polymer composites in plastics packaging	Polymer composites in plastics packaging
	Sensors	Anti-static coatings	Transparent barrier films in food packaging
	Aerospace composites	Transparent barrier films in food packaging	Rheology modifiers
	Medical implants	Self-cleaning coatings	Paper composites
	Drilling fluids in oil and gas	Filtration membranes	Hygiene products
		Insulation	Filter media
		Paint additives	
		3D printing additives	
		Automotive composites	
		Drilling fluids in oil and gas	
n =	**7**	**12**	**8**
Cerium Oxide	Conductive coatings	Solid oxide fuel cells	Polishing slurries
	Sensors	Anti-corrosion additives	UV absorbers
	Hydrogen production		Fuel additives
	Bioscaffolds		Catalysts
	Therapeutic agents		
	Catalytic antioxidants		
n =	**6**	**2**	**4**
Clays	Medical implants	Medical implants	Barrier films in packaging
	Water filtration	Water filtration	Automotive composites
			Automotive tire additives
			Rheology modifiers

ENM	Applied R&D	Demonstration	Commercial
			Flame retardant plastic additives
n =	**2**	**2**	**5**
Cobalt Oxide	LIB electrode additives	LIB electrode additives	Magnetic fluids
	Electrochromic devices	Electrochromic devices	Catalysts
	Sensors	Sensors	
	Drug delivery & cancer therapy		
n =	**4**	**3**	**2**
Copper Oxide	Field emission devices	Gas sensors	Industrial catalysts
	Super hydrophobic coatings	Anti-microbials	Semiconductor additives
	Thin film solar cells	Anti-oxidants	
	Filtration	Groundwater treatment	
	Gas sensors	LIB additives	
		Thin film solar cells	
		Filtration	
n =	**5**	**7**	**2**
Dendrimers	Gene therapy	Drug delivery/ cancer therapy	Antimicrobial agents in sexual health
	Catalytic agents	Water repellent coatings	Cosmetics
	Separating agents	Gene therapy	Antibody reagents
	Chelating agents	Catalytic agents	Medical imaging
	Water treatment	Separating agents	Inkjet inks
	Chemical sensors		Water repellent coatings
	Light harvesting		
n =	**7**	**5**	**6**
Diamonds	Drug & gene delivery	Polymer composites	Lubricants
	MRI contrast agents	MRI contrast agents	Polishing slurries
		Thermal compounds (pastes) for electronics	Anti-friction & wear coatings
			Thermal compounds (pastes) for electronics
n =	**2**	**3**	**4**
Fibers	Biosensors	Biosensors	Air/ liquid filtration membranes
		Battery separators	Medical textiles (hydrogel dressings)
		Conductive additives for energy storage	Bone/ skin regeneration
		Medical textiles (hydrogel dressings)	
		Bone/ skin regeneration	
n =	**1**	**5**	**3**
Fullerenes	Electron acceptors in polymer-based solar	Electron acceptors in polymer-based solar	Lubricant additives
	Polymers in supercapacitors	Polymers in supercapacitors	Whitening and anti-aging cosmetics
	Fuel cell catalyst	Fuel cell catalyst	Drug delivery
	Medical imaging	Medical imaging	
		Drug delivery	
		Lubricant additives	
n =	**4**	**6**	**3**

ENM	Applied R&D	Demonstration	Commercial
Gold		MRI contrast agents	Biosensors
		Electronics	MRI contrast agents
		Cancer therapy and drug delivery	
		Gas sensors	
		Water remediation	
n =	**0**	**5**	**2**
Graphene	Antibacterials	Thermal barrier	Antistatic coatings
	Optical switches	Supercapacitor additives	Battery additives
	Field effect transistors	Anti-corrosion coatings	Sporting goods
	Medical device coatings	Anti-icing coatings	Tires
	MRI contrasts agents	Antibacterials	Oilfield chemicals
	Stress strain actuators	Photodetectors	Water filtration membranes
		Water filtration membranes	Electron microscopy sample supports
		Inks &3D printed materials	Polymer composites
		Thermal management	Conductive inks
		Cement additives	Conductive additives for displays
		Adhesives	Humidity sensors
		Biosensors	Inks & 3D printed materials
		Lubricants	EMI shielding
		Flame retardants	
		Paints & coatings	
		Barriers and impermeable films	
n =	**6**	**16**	**13**
Iron Oxide	Fuel cell catalysts	Cancer therapy & drug delivery	Magnetic storage media
	Thermochromic smart windows	Magnetic bioseparation	MRI contrast agents
		Immunoassays	Polishing media
		Hyperthermia agents	
		Propellants	
		Environmental remediation	
		Magnetic coatings	
		Biosensors	
		MRI contrast agents	
n =	**2**	**9**	**3**
Magnesium Oxide	IR attenuation films and coatings	Fuel additives	Catalysts
	Antibacterials	High-temperature dehydrating agents	Flame retardants
	Cancer therapy	Superconductors	Refractory material in furnace linings
	Gas sensors	Fuel additives (e.g. rocket propellants)	
	Adsorbent for toxic chemical agents	IR attenuation films and coatings	
		Antibacterials	
		Gas sensors	

ENM	Applied R&D	Demonstration	Commercial
		Adsorbent for toxic chemical agents	
n =	**5**	**8**	**3**
Manganese Oxide	Electrocatalysts	MRI contrast agents	
	Water purification	Anode materials in LIBs	
	Supercapacitor additives	Water purification	
	Biosensors	Supercapacitor additives	
	Electrochemical sensors	Biosensors	
		Electrochemical sensors	
n =	**5**	**6**	**0**
Nickel	Catalysts	Magnetic fluids	
	Conductive coatings	Propellant additives	
	Electrochromic coatings	Catalysts	
		Conductive coatings	
		Electrochromic coatings	
n =	**3**	**5**	**0**
Quantum Dots	Quantum switches/ quantum computing	Thin film solar cells	Edge optic LCDs in TVs
	Printable solar cells	On chip LCDs in TVs	On surface LCDs in TVs
	Thin film solar cells	Medical contrast agents	Medical contrast agents
	Solar windows	Biosensors	Security inks & tags
	Drug delivery	Infrared imaging	Image sensors
		Security inks & tags	
		QD lasers	
n =	**5**	**7**	**5**
Silicon Dioxide	Sensors	Catalysts	Rubber and plastic additives
		Silicon nanowires in electronics	Coating additives
		Sensors	Cosmetics additives
			Fillers in nanocomposites
			Structural adhesives
			Automotive tire additives
			Cement additives
n =	**1**	**3**	**7**
Silver	Smart glass	Smart glass	Antimicrobial wound care
		Water filtration & purification	Antimicrobial medical devices
			Textiles
			Antimicrobial coatings
			Cosmetics & personal care additives
			Conductive inks & films
			Food packaging
			Water filtration & purification
n =	**1**	**2**	**8**
Titanium Dioxide	Microfluidic devices	Theranostics	Photovoltaics (dye-sensitized solar cells)

ENM	Applied R&D	Demonstration	Commercial
	Non-volatile memristive devices	Solar fuel generation via water splitting	Sunscreens & cosmetics
	Solar fuel generation via water splitting	Photocatalysts for environmental	Photocatalytic self-cleaning coatings
	Theranostics		
n =	**4**	**3**	**3**
Zinc Oxide			Sunscreens & cosmetics
			UV absorbers for paints, coatings, plastics/ synthetics & textiles
			Antimicrobial and bacteriostatic agent
			Adhesives
			Electrically conductive applications
n =	**0**	**0**	**5**
Zirconium Oxide	Cancer diagnostics	Fuel cell additives	Resins for optics
		Biomedical implant coatings	Thermal barrier coatings
		Dental composites	Ceramics additives
		Polymer additives	Refractory products
			Cement additives
			Catalysts
			Oxygen sensors
n =	**1**	**4**	**7**

Table S3. Technology readiness level[1]

Engineered Nanomaterial Global Production Volumes (Mg)

ENM	ENM Formula	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Aluminum Oxide	Al_2O_3	4250-7800	4400-8200	4500-8750	4725-9400	4960-10100	5200-10870	5500-11700	5750-12550	6000-13500	6400-14650	6800-15900	7250-17300	7750-18900	8300-20600	8800-22450	9500-24450
Antimony Tin oxide	SnO_2/Sb_2O_5 (90%/10% wt.)	90-160	95-170	100-185	110-200	120-225	130-255	140-290	150-320	165-360	180-410	195-460	210-505	225-555	240-610	260-670	275-740
Bismuth oxide	Bi_2O_3	25-32	27-37	30-43	32-49	35-57	37-67	40-80	43-88	46-97	52-108	58-118	61-130	65-143	70-170	75-188	80-205
Carbon nanotubes	C	350-1700	400-1700	400-2000	450-2200	520-2500	550-2750	585-2850	615-3150	650-3300	685-3500	710-3750	750-4000	785-4300	810-5700	850-6100	915-7000
Cellulose	$(C_6H_{10}O_5)_n$	17-17	41-41	90-175	200-380	300-800	345-1120	415-1570	500-2195	600-3077	735-4149	910-5600	1140-7560	1420-10210	1175-13270	2200-17250	2775-24150
Cerium oxide	CeO_2	750-1000	788-1090	800-1188	830-1295	880-1412	933-1539	989-1677	1048-1828	1111-1993	1177-2172	1248-2367	1323-2580	1402-2813	1486-3066	1576-3342	1670-3642
Clays	-	23000-40000	24000-44000	24600-46200	25200-48510	26000-51200	26500-54000	27300-57250	28100-60650	29000-64300	30000-68200	31000-72300	31500-77000	33000-82000	34000-87300	35250-93000	36500-99000
Cobalt oxide	Co_3O_4	4.8-7.0	4.8-7.0	4.9-7.5	5.0-8.0	5.2-8.5	5.4-9.0	5.6-9.5	5.9-10.1	6.2-10.7	6.5-11.7	6.8-13.0	7.2-14.4	7.5-16.0	7.9-17.7	8.3-19.7	8.7-21.8
Copper oxide	CuO	200-330	220-380	240-440	270-490	290-570	320-640	350-710	385-790	420-900	460-1030	500-1150	550-1220	610-1270	680-1350	750-1450	830-1600
Dendrimers	-	0.20-0.80	0.25-0.90	0.28-1.00	0.31-1.12	0.34-1.25	0.37-1.48	0.40-1.75	0.44-2.06	0.48-2.43	0.54-2.97	0.60-3.62	0.67-4.52	0.75-5.66	0.83-7.07	0.93-8.84	1.03-11.05
Diamonds	C	8.0-10.0	8.8-11.3	9.7-12.7	10.7-14.3	12-16.2	13.5-18.3	15.2-20.8	17.1-23.7	19.3-27.3	21.8-31.4	24.6-36.4	27.8-42.2	31.4-49	35.5-57.3	40.1-67.1	46.2-79.1
Fibers	-	110-170	130-220	150-250	162-275	175-308	192-354	212-407	233-468	260-539	290-628	323-731	365-874	412-1044	474-1248	545-1491	627-1797
Fullerenes	C	20-45	25-60	30-75	35-81	40-98	50-115	60-132	73-148	87-165	100-183	112-204	123-231	136-260	149-294	164-333	180-376
Gold	Au	0.8-1.8	0.9-2.0	1.0-2.0	1.0-3.0	1.1-3.0	1.3-3.1	1.5-3.2	1.8-3.4	2.0-3.7	2.2-4.0	2.4-4.3	2.8-4.7	3.1-5.1	3.4-5.5	3.8-5.9	4.3-6.3
Graphene	C	0.25-1.5	0.25-3	0.5-10	0.7-25	1-40	1.5-75	2-125	3-175	5-240	7-310	10-400	20-525	45-650	60-800	85-925	115-1050
Iron oxide	Fe_2O_3/Fe_3O_4	4.5-13	5-22	5.8-33	7-38	8.1-45	9.2-54	10.7-69	15-82	19.5-97	24.5-115	32-132	36.8-161	42.3-197	48.7-240	56-292	64-357
Magnesium oxide	MgO	6-14	7.2-17.5	10-20.3	13-25.5	15-31.7	18.5-38	21-46	25-54.5	31-63	37-75	44-93	48.4-107	53-123	59-141	64-162	71-187
Manganese oxide	Mn_2O_3	1.4-1.8	1.4-2.2	1.6-2.6	1.8-3.1	2-3.5	2.4-4.2	2.4-5	2.8-6	3.3-7.1	3.7-8	4.3-8.7	4.7-10	5.2-11.5	5.6-13.2	6.2-15.2	6.8-17.5
Nickel	Ni	4.0-11.0	4.1-12.1	4.2-13.9	4.4-16.0	4.6-19.2	4.9-23.0	5.1-27.7	5.4-33.2	5.6-39.8	5.9-47.8	6.3-58.5	6.6-71.7	7.0-87.8	7.4-109.8	7.8-137.2	8.3-171.6
Quantum dots*	-	-	-	-	-	-	-	>0.5	-	-	-	>5	-	-	-	-	-
Silicon oxide	SiO_2	120000-700000	130000-800000	140000-930000	155000-1150000	185000-1400000	210000-1600000	240000-1900000	280000-2200000	320000-2500000	365000-2800000	400000-3150000	440000-3300000	480000-3600000	496800-3888000	514188-4199040	532185-4534963
Silver	Ag	90-320	100-350	110-370	120-390	135-420	150-450	165-475	185-500	210-530	230-560	255-600	280-635	310-670	350-710	380-753	410-798
Titanium dioxide	TiO_2	30000-120000	30600-130000	31500-135000	32150-142000	33000-148000	34000-160000	35000-174000	36000-190000	37250-210000	38500-225000	40000-245000	42000-268000	43500-290000	45560-325000	47500-364000	49500-497000
Zinc oxide	ZnO	6000-30000	6000-30000	6150-31500	6250-31500	6390-32300	6845-34720	7190-37500	74560-40500	7960-43740	8440-47460	8945-51500	9525-55870	10145-60890	10800-66900	11500-73000	12250-79954
Zirconium oxide	ZrO_2	1375-31000	1375-32000	1400-32000	1450-33000	1500-35000	1545-36400	1591-37856	1639-39370	1688-40945	1739-42583	1791-44286	1845-46058	1900-47900	1957-50055	2016-52308	2097-54662

Table S4. Global production volume estimates from low to high in Mg. *The quantum dot market was not reported on a mass basis, with the exception of 2016 and 2020 estimates. Global quantum dot revenues for the years 2013, 2015, and 2025 (projection), respectively: **$40-80M; $400-600M; $8,000-10,000M** (from low to high estimates and rounded to one significant digit). Data adapted from *The Global Nanotechnology and Nanomaterials Market Opportunity Report*[1] .

Element	Ore Production 2014 (Gg)	ENM Production Volume 2014 (Gg)	Nano Fraction of Ore Production (%)
Ag	33.4	0.4	1%
Al	67590	5	0.008%
Ce	63.6	1	2%
Co	246	0.006	0.003%
Cu	22397	0.5	0.002%
Fe[a]	1645642	0.03	0.000002%
Fe[b]		0.03	0.000002%
Ni	2814	0.02	0.0007%
Zn	15294	26	0.2%

Table S5. Nanomaterial production volumes are based on the high 2014 estimates. All values are in metal content of the particular element; nanomaterial metal content is calculated based on assumed chemical formulas listed in Table S6. Iron composition of nanomaterial is calculated based on the assumption that the total composition of the reported production volume is (a) Fe_2O_3 or (b) Fe_3O_4.

SUMMARY OF GLOBAL ANTHROPOGENIC MATERIAL EFFICIENCIES

Element	Cycle Year	Ore Production	Enters Fabrication, Manufacturing, & Use	Total Production Losses	Fabrication & Manufacturing Losses	In-use Dissipation	Recycling	Non-functional Recycling	Dissipation	Landfill, Dispersion and/or Incineration	Other Repository	Processing or Separation Loss	Nano
		100%	73%	27%			42%		11%	21%			1%
Ag (Gg)	2014	33.4	24.5	8.94			13.9		3.67	6.99			0.4
		100%	79%	21%		5%	41%			19%	13%	1%	0.008%
Al (Gg)	2014	67600	53400	14200		3360	27400			13100	8950	559	5
		100%	72%	28%	10%					62%			2%
Ce (Gg)	2014	63.6	45.9	17.7	6.66					39.2			1
		100%	37%	63%			8%	3%		26%			0.003%
Co (Gg)	2014	246	91.3	154			20.3	8.21		62.8			0.006
		100%	82%	18%		3%	27%			38%		12%	0.002%
Cu (Gg)	2014	22400	18300	4110		756	6120			8620		2800	0.5
		100%	83%	17%		2%	61%			19%			0.000002%
Fe (Gg)	2014	1650000	1360000	285000		41100	1000000			316000			0.03
		100%	71%	29%			45%	11%		15%			0.0007%
Ni (Gg)	2014	2810	1990	820			1260	322		414			0.02
		100%	82%	18%		11%	33%			38%			0.2%
Zn (Gg)	2014	15300	12500	2800		1660	5040			5800			26

Table S6. All masses are rounded to three significant digits with the exception of nanomaterial flows.

Element	Data Source	2014 World Mine, Smelter, and/or Refinery Production (Gg)	Data
Ag	U.S. Geological Survey Minerals Yearbook 2014[5]	Mine Production: 26.8	Includes data available through April 4, 2016.
Al	U.S. Geological Survey Minerals Yearbook 2015[7]	Primary Smelter Production: 54000	Includes data available through October 6, 2016
Au	U.S. Geological Survey Mineral Commodity Summaries 2016[25]	Mine Production: 2.99	Published January 2016
Bi	U.S. Geological Survey Minerals Yearbook 2015-Advance Data Release[26]	Mine Production: 10.6	Includes data available through August 8, 2016.
Ce	U.S. Geological Survey Minerals Yearbook 2014[11]	Mine Production: 50.9	Includes data available through August 26, 2016.
Co	U.S. Geological Survey Minerals Yearbook 2014[13]	Mine Production: 123 Primary Refinery Production: 91.3	Includes data available through November 2, 2015.
Cu	U.S. Geological Survey Minerals Yearbook 2014[15]	Mine Production: 18500 Primary Refinery Production: 18300	Includes data available through May 9, 2016.
Fe	U.S. Geological Survey Minerals Yearbook 2014-Preliminary[18]	Mine Production: 1430000	Includes data available through December 15, 2015.
Mg	U.S. Geological Survey Mineral Commodity Summaries 2016[27, 28]	Magnesite Mine Production: 8420 Primary Metal Production: 970	Published January 2016
Mn	U.S. Geological Survey Mineral Commodity Summaries 2016[29]	Mine Production: 17800	Published January 2016
Ni	U.S. Geological Survey Mineral Commodity Summaries 2016[20]	Mine Production: 2450	Published January 2016
	International Nickel Study Group, World Nickel Statistics 2015[21]	Primary Smelter Production: 1990	Includes data available through August 27, 2015
Sb	U.S. Geological Survey Mineral Commodity Summaries 2016[30]	Mine Production: 158	Published January 2016
Si	U.S. Geological Survey Mineral Commodity Summaries 2016[31]	Silicon Production: 8110	Published January 2016
	U.S. Geological Survey Minerals Yearbook 2014[32]	Silicon Metal Production: 2600	Includes data available through July 30, 2015.
Sn	U.S. Geological Survey Mineral Commodity Summaries 2016[33]	Mine Production: 286	Published January 2016
Ti	U.S. Geological Survey Mineral Commodity Summaries 2016[34]	Mine Production: 3620	Published January 2016
Zn	U.S. Geological Survey Minerals Yearbook 2014[23]	Mine Production: 13300	Includes data available through November 5, 2015.
Zr	U.S. Geological Survey Minerals Yearbook 2014[35]	Mine Production: 671	Includes data available through April 21, 2016.

Table S7. All values expressed in content of particular element and rounded to three significant digits. CeO_2 content of rare earth oxides assumed to be 50%[8,9]; approximate cobalt primary refinery production; total magnesium production is assumed to be the sum of magnesite mine production and Mg metal; a fraction of Mg metal is produced from magnesite; dolomite ore production not available; Si content of Si metal assumed to be ca. 100%; Ti mine production is the combination of ilmenite and rutile; ZrO_2 content of Zr mineral concentrates assumed to be ca. 63%[24].

References (SI)

1 Future Markets Inc., *The Global Market for Nanotechnology and Nanomaterials*, 2016.
2 F. Cardarelli, *Materials handbook*, Springer-Verlag London Limited, 2008.
3 B. K. Reck and T. E. Graedel, *Science (80-.).*, 2012, **337**, 690–695.
4 J. Johnson, J. Jirikowic, M. Bertram, D. Van Beers, R. B. Gordon, K. Henderson, R. J. Klee, T. Lanzano, R. Lifset, L. Oetjen and T. E. Graedel, *Environ. Sci. Technol.*, 2005, **39**, 4655–4665.
5 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Silver, Vol. I. Metals and Minerals*, 2016.
6 G. Liu, C. E. Bangs and D. B. Müller, *Nat. Clim. Chang.*, 2012, **3**, 338–342.
7 U.S. Geological Survey, *2015 USGS Minerals Yearbook, Aluminum, Vol. I. Metals and Minerals*, 2016.
8 D. I. Bleiwas and J. Gambogi, *USGS Preliminary Estimates of the Quantities of Rare-Earth Elements Contained in Selected Products and in Imports of Semimanufactured Products to the United States, 2010*, 2013.
9 L. Z. H. I. Li and X. Yang, *1st Eur. Rare Earth Resour. Conf.*, 2014, 26–36.
10 X. Du and T. E. Graedel, *Sci. Rep.*, 2011, **1**, 145.
11 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Rare Earths, Vol. I. Metals and Minerals*, 2016.
12 E. M. Harper, G. Kavlak and T. E. Graedel, *Environ. Sci. Technol.*, 2012, **46**, 1079–1086.
13 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Cobalt, Vol. I. Metals and Minerals*, 2016.
14 S. Glöser, M. Soulier and L. A. Tercero Espinoza, *Environ. Sci. Technol.*, 2013, **47**, 6564–6572.
15 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Copper, Vol. I. Metals and Minerals*, 2016.
16 International Copper Study Group, *The World Copper Factbook*, 2015.
17 T. Wang, D. B. Muller and T. E. Graedel, *Environ. Sci. Technol.*, 2007, **41**, 5120–5129.
18 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Iron Ore, Vol. I. Metals and Minerals*, 2017.
19 B. K. Reck and V. S. Rotter, *J. Ind. Ecol.*, 2012, **16**, 518–528.
20 P. H. Kuck, *2016 USGS Mineral Commodity Summaries, Nickel*, 2016.
21 International Nickel Study Group (INSG), *World Nickel Statistics 2015*, 2015.
22 G. Meylan and B. K. Reck, *Resour. Conserv. Recycl.*, 2015, 1–10.
23 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Zinc, Vol. I. Metals and Minerals*, 2016.
24 H. Elsner, *Zircon – insufficient supply in the future?*, Berlin, The German Mineral Resources Agency (DERA), Federal Institute for Geosciences and Natural Resources, 2013.
25 M. W. George, *2016 USGS Mineral Commodity Summaries, Gold*, 2016.
26 U.S. Geological Survey, *2015 USGS Minerals Yearbook, Bismuth, Vol. I. Metals and Minerals*, 2017.

27 E. Lee Bray, *2016 USGS Mineral Commodity Summaries, Magnesium Metal*, 2016.
28 E. L. Bray, *2016 USGS Mineral Commodity Summaries, Magnesium Compounds*, 2016.
29 L. A. Corathers, *2016 USGS Mineral Commodity Summaries, Manganese*, 2016.
30 D. E. Guberman, *2016 USGS Mineral Commodity Summaries, Antimony*, 2016.
31 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Silicon, Vol. I. Metals and Minerals*, 2016.
32 Emily K. Schnebele, *2016 USGS Mineral Commodity Summaries, Silicon*, 2016.
33 C. S. Anderson, *2016 USGS Mineral Commodity Summaries, Tin*, 2016.
34 G. M. Bedinger, *2016 USGS Mineral Commodity Summaries, Titanium Mineral Concentrates*, 2016.
35 U.S. Geological Survey, *2014 USGS Minerals Yearbook, Zirconium and Hafnium, Vol. I. Metals and Minerals*, 2016.