Supporting Information

A dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators & uncertainty evaluation

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In the following, we provide detailed information of the global copper flow model concerning input data, assumptions and the applied methodology including the derivation of key equations. As described in the corresponding paper, it is a dynamic stock-and-flow model featuring a closed mass balance at every node and at every time step. There are five conceptual "life stages" considered in the model: primary production, manufacturing, use, waste management and environment. Through the model, it is possible to access all relevant copper flows to estimate recycling indicators over time. A depiction of the model is given in Figure S1.

Input data to the model and data sources

Historical data on copper mining, production and use were used to estimate current waste and recycling flows and to account for copper stocks in use and in landfills. Because several copper applications remain in the use phase for several decades and exhibit broad lifetime distributions, historical production data for the past century (1910-2010) were utilized to simulate current waste flows. Table S1 gives an overview of the data sources for historical copper production.

Table S1: Timeframe and sources for input into the model. Acronyms: ICA (International Copper Association), IWCC (International Wrought Copper Council), USGS (US Geological Survey, ICSG (International Copper Study Group), BGS (British Geological Survey), BGR (Bundesanstalt für Geowissenschaften und Rohstoffe))) (*1–5*).

Flow / Stock	Timeframe	Source
Mining / Primary copper production		
Annual global mine production	1910-1960	US Bureau of Mines / Ayres 2003
Annual global mine production	1960-2010	USGS / ICSG / BGS / BGR
Refined copper use / refined copper production		
Annual global refined copper production	1910-1960	Ayres 2003
Annual global refined copper production	1960-2010	ICSG / USGS / BGS
Annual global refined copper use	1960-2010	ICSG / USGS
Semis production		
Annual total semis production	1950-2010	ICSG
Detailed dataset of semis production	2006-2010	ICA / IWCC
Allocation of copper in end use products		
End-use sectors of copper	1912-2008	ICSG / Ayres 2003
Detailed dataset of end-use sectors	2006-2010	ICA Dataset

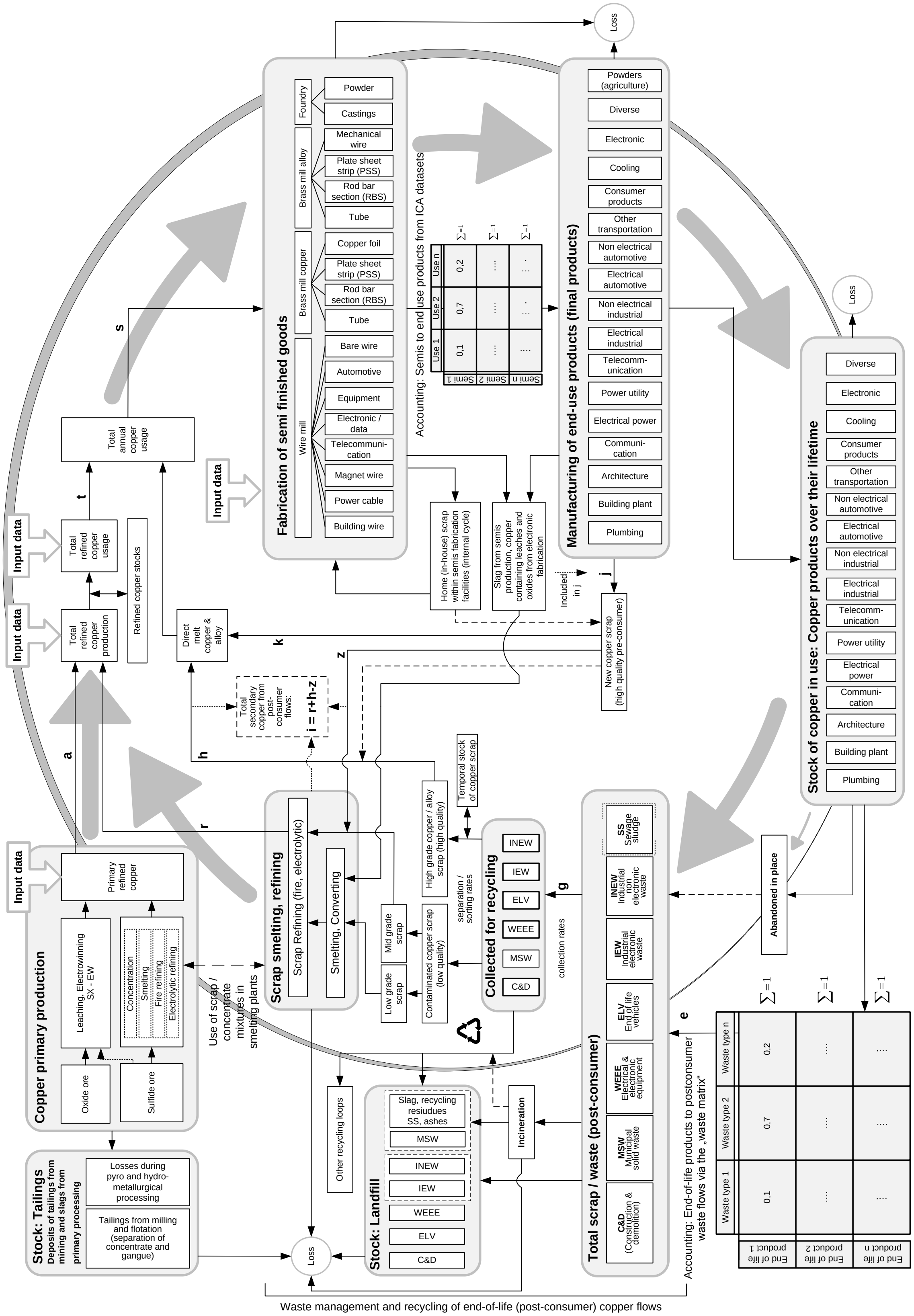


Figure S1: Structure of the global copper flow model. For more information see corresponding paper

The main input flows to the model are primary copper production coming from mining, total refined copper production (copper cathodes through electrolytic refining) which already includes parts of secondary copper (see Figure S1) and the fabrication of semi-finished goods for which both new scrap coming from fabrication and high grade EoL scrap are directly remelted together with copper cathodes (cf. Figure S2 and Table S2).

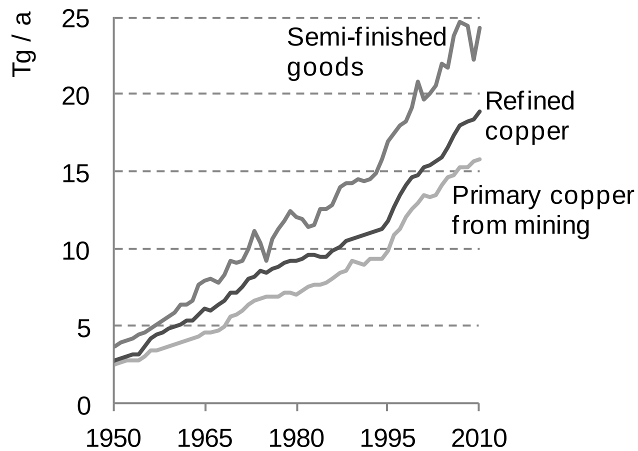


Figure S2: Main input flows to the model in historical perspective (annual production data from ICSG, ICA, USGS (*1*, *4*)).

Survey

The assumptions on fabrication efficiencies, mean average lifetimes and lifetime distributions of different end-use applications, separating and sorting efficiencies within the waste management (see corresponding tables below), etc. were challenged and refined by conducting a global expert survey. In Table S3 we provide information on the interviews and interviewees.

Table S2: Main input data to the model: mining data, production data of refined copper and semi-finished goods fabrication (*1*, *3–5*). All figures in thousand metric tons.

year	mining	refinery production	semis fabrication	year	mining	refinery production	semis fabrication	year	mining	refinery production	semis fabrication
1910	850	872	1166	1944	1534	1626	2946	1978	7143	9030	11806
1911	865	887	1206	1945	1769	1873	2989	1979	7206	9200	12376
1912	994	1019	1370	1946	1802	2000	3115	1980	7064	9261	12029
1913	957	982	1326	1947	2173	2400	3316	1981	7327	9319	11898
1914	903	926	1231	1948	2265	2577	3517	1982	7552	9573	11349
1915	1032	1058	1423	1949	2211	2500	3618	1983	7669	9541	11585
1916	1342	1376	1854	1950	2462	2700	3657	1984	7720	9440	12567
1917	1407	1443	1924	1951	2595	2888	3875	1985	7819	9455	12593
1918	1360	1395	1874	1952	2697	2964	4020	1986	8079	9920	12785
1919	1024	1050	1417	1953	2732	3100	4221	1987	8397	10148	13934
1920	943	967	1291	1954	2781	3200	4391	1988	8575	10512	14240
1921	515	528	697	1955	3034	3700	4623	1989	9163	10687	14198
1922	841	863	1161	1956	3383	4200	4824	1990	9061	10804	14567
1923	1219	1250	1685	1957	3467	4400	5125	1991	8921	10908	14346
1924	1298	1331	1779	1958	3559	4600	5326	1992	9326	11045	14528
1925	1375	1410	1884	1959	3601	4800	5579	1993	9376	11124	14858
1926	1423	1459	1965	1960	3826	4998	5917	1994	9381	11239	15772
1927	1455	1492	2004	1961	3979	5127	6331	1995	9906	11832	16960
1928	1535	1574	2119	1962	4110	5296	6363	1996	10903	12677	17534
1929	1555	1595	2127	1963	4179	5400	6637	1997	11340	13478	18041
1930	1362	1397	1877	1964	4331	5739	7606	1998	12046	14075	18230
1931	1113	1142	1540	1965	4531	6059	7877	1999	12562	14578	19121
1932	875	897	1192	1966	4510	6004	8058	2000	12989	14796	20833
1933	983	1008	1356	1967	4755	6324	7837	2001	13532	15273	19691
1934	1235	1267	1708	1968	4891	6653	8339	2002	13358	15354	20052
1935	1430	1467	1961	1969	5568	7137	9205	2003	13419	15638	20589
1936	1654	1696	2263	1970	5671	7212	9040	2004	14120	15928	22041
1937	1968	2018	2709	1971	5958	7592	9198	2005	14682	16573	21775
1938	1555	1595	2515	1972	6391	8100	9955	2006	14750	17295	23758
1939	1362	1397	2540	1973	6580	8187	11161	2007	15218	17944	24636
1940	1113	1142	2598	1974	6758	8544	10358	2008	15288	18200	24407
1941	1106	1140	2624	1975	6841	8400	9199	2009	15631	18356	22218
1942	1189	1257	2658	1976	6937	8759	10627	2010	16100	18966	24368
1943	1255	1297	2903	1977	6937	8884	11260				

Table S3: Interview partners to cross-check the data and assumptions. Each interview took around 1 hour and was carried out by going through the concept of the model, the data derived from literature, and capturing personal statements, assessments, assumptions and opinions from the interviewee.

Nr. of interviews	Institution	Region
2	Copper Development Association	Asia
1	Deutsches Kupferinstitut	Europe
3	European Copper Institute	Europe
3	Copper smelter and refiner (primary & secondary)	Global
2	Semi-finished goods fabricator	Global
1	International Wrought Copper Council	Global
1	Institute of Scrap Recycling Industries	Global
1	Copper Development Association	Latin America
1	U.S. Geological Survey	North America
1	Copper Development Association	North America
1	International Copper Study Group	Global

Detailed description of the model

The global copper flow model comprises five conceptual "life stages": primary production, manufacturing, use, waste management and environment. In the following section, we provide a detailed description all stages and the key assumptions and data in conjunction with these "stages of life".

Primary copper production

The model, as implemented and shown in Figure S1, uses data for primary refined copper production as the starting point of the simulation. The flows for the processing steps depicted in Figure S1 are calculated backward based on production data of primary refined copper. It should be noted that during the smelting of concentrates, copper-containing scrap is often added to the melt. Thus, the smelting and refining of primary and secondary copper are in many cases physically not separable—particularly in industrialized countries with high amounts of available copper scrap. However, because the mass flows from mining are reported and used as input data, a separate simulation of primary and secondary flows, as shown in Figure S1, is possible.

To better understand how the global copper flow model maps to physical reality, it is useful to briefly review the production of primary copper—shown schematically in Figure S3. There are two ways of processing primary copper depending on the kind of ore. The pyrometallurgical process accounts for 82% of the copper production (*1*), and is used for sulphidic ores which is the most important group, representing 90% of the economically workable copper deposits. Chalcopyrite, covellite and chalcocite are some of the most common copper containing minerals within sulphidic ores (*6*). The first step in the pyrometallurgical process is the production of copper concentrate by flotation of the crushed ore. Both the crushing procedure and the flotation have efficiencies slightly above 90% (*7*, *8*), so that during these steps, $\approx$ 18% of the copper content in the exploited ore is lost to tailings and to the pulp (*9*). The following steps take place in several smelting furnaces where the iron and sulfur fractions are removed from the melt and the copper concentration is increased. During the smelting processes, about 3% of the copper feed within the concentrates is lost to furnace slag (*6*). In the following electrolytic refining the remaining impurities are eliminated and cathode copper is obtained with an efficiency of around 99% (*9*). It has to be considered that during the smelting of concentrates, copper-containing scrap is often added to the melt. Thus, the smelting and refining of primary and secondary copper are in many cases physically not separable—particularly in industrialized countries with high amounts of available copper scrap. However, because the mass flows from mining are reported and used as input data, a separate simulation of primary and secondary flows is possible.

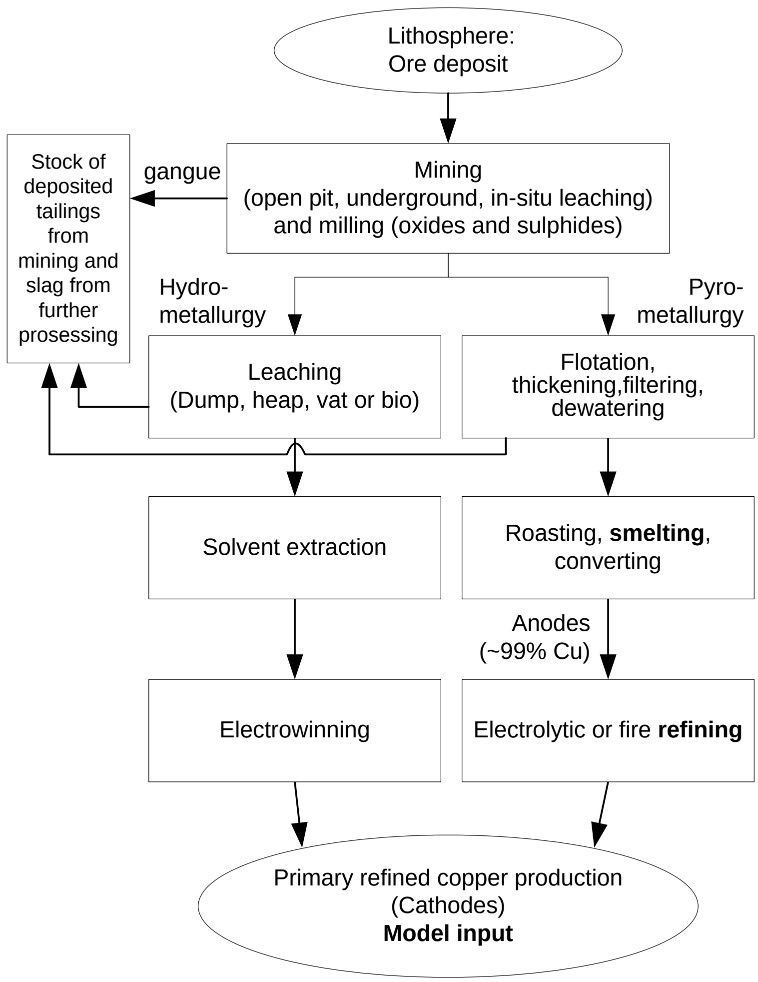


Figure S3: Simplified process scheme for the primary production of copper from copper ores (oxides and sulphides). Notice that during smelting and refining (bold), copper scrap is usually processed together with primary copper. However, the recovery of copper from scrap is treated separately in the model.

The SXEW-process (solvent extraction / electrowinning) is the second way of processing copper ore. It is a hydrometallurgical treatment which is mostly used for oxide ores like cuprite, but there are approaches to use sulfide ores as well (*2*). The ore is first leached with sulfuric acid, dissolving $\approx 85\%$ of the original copper contained in the ore (*10*). Then a solvent is added to obtain a copper-rich solution. In a last process step, primary refined copper is produced by electrowinning with a loss rate of around 0.5% (*8*). Notice that there is no mixing of primary + secondary copper in this production process.

Manufacturing

This stage includes the fabrication of semi-finished goods and end-use products (for sources see Table S1). The structure of the more detailed datasets for 2006-2010 is shown graphically in the Figure S4.

The balancing of primary (coming from the primary production/mining stage) and secondary (coming both from the manufacturing and waste management processes) copper flows in the manufacturing stage is satisfied by defining the collection rates of EoL scrap as a function of total annual copper use (see "Waste management", below).

To reflect the fact that there is scrap produced during the fabrication of semi-finished goods (resulting e. g. from edge trimmings or off-spec production) and final products (e. g. in the form of turnings, stampings and cuttings), two loops were integrated into the model (see Figure S1):

1. A loop describing the internal copper recycling process within facilities producing semi-finished goods (usually called "home scrap"). In general, this copper flow does not leave the facilities and is therefore of no consequence to the rest of the model. This loop is not considered as "new scrap" and does not influence the calculated recycling indicators.

2. An outflow of "new scrap" (or "pre-consumer scrap") going out from the manufacturing of final products (final products). This new scrap is mostly returned (approx. 80%) to the facilities producing semi-finished goods and is directly remelted. The rest enters the waste management system, where it is again separated into copper and alloy that can be directly

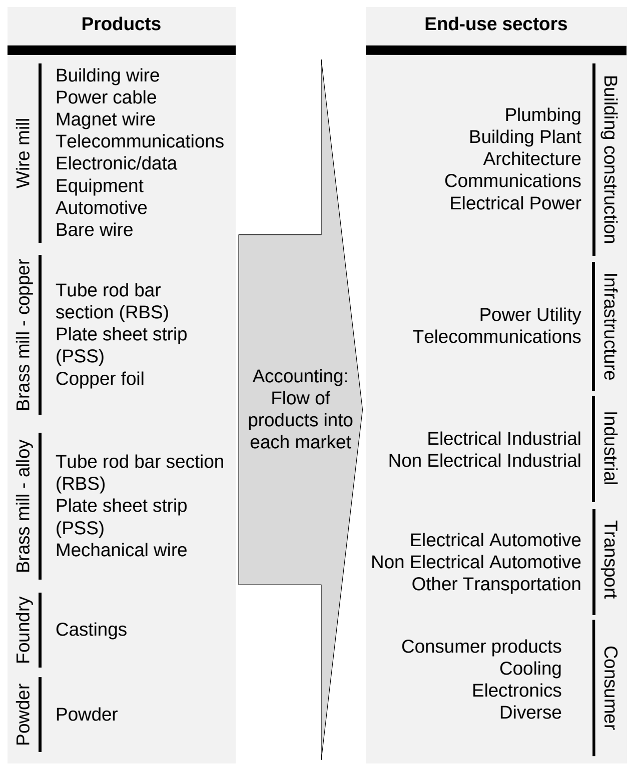


Figure S4: Structure of the ICA/IWCC yearly copper demand datasets. The different end-use sectors are defined as follows: Plumbing: water distribution, heating, gas, sprinklers / Building Plant: air conditioning and tubes / Architecture: roofs, gutters, flashing, decoration, builders / Communications: wiring in buildings / Electrical Power: power distribution, earth, ground, light, wire device; Telecommunications: Telecommunication network / Power Utility: Power transmission and distribution network / Electrical Industrial: Industrial transformers and motors / Non Electrical Industrial: Valves, fittings, instruments and plant equipment / Electrical Automotive: Harnesses, motors, automotive electronics / Non Electrical Automotive: Radiators and tubing / Other Transport: Railroad, shipping and marine / Consumer and general products: Appliances, instruments, tools and other / Cooling: Air conditioning and refrigeration / Electronic: Industrial and commercial electronics and PCs / Diverse: Ammunition, clothing, coins and other.

remelted (10% of total new scrap) and copper or alloy that is processed (10% of total new scrap) together with EoL scrap prior to being smelted and refined. Comparable data have been published for regional models (*11*, *12*).

Assumptions for the fabrication efficiencies (used to estimate new scrap generation) of different end-use applications are shown in Table S4. Although these fabrication efficiencies might appear low at first sight, several processing steps such as punching, stamping, milling, shaping, cutting, etc. lead to comparatively high material losses in the form of high-grade new scrap. The value of this scrap is generally high because the scrap is usually of high purity and the composition of alloys is precisely known. As a result, most fabricators hold contracts with their semis suppliers for the processing of this scrap. Within this framework, fabricators only pay the extra costs for remelting and reprocessing of their recycled new scrap, saving the cost of the raw material.

Because of market and price volatility and the fact that both governments and industries seek security of short-term supply, temporary stocks of copper cathodes, copper scrap and copper semi-finished goods exist. We note that the volume of these stocks and particularly the annual changes of the stock volume are very small compared to the overall copper market. Nevertheless, we sought to take these stocks into account as far as the data permit or a suitable approach could be found. As illustrated in Figure S1, both temporary stocks for refined copper (copper cathodes) and stocks for directly meltable high grade scrap are implemented in the model. In the case of copper cathodes, annual stock changes are derived from published data for refined copper production and refined copper demand (*1*). In the case of copper scrap, stock changes are estimated (see below). Furthermore, it has to be considered that some of the cathode demand might go into non liquid strategic stocks which are held by governments and which are often not reported. As these stocks only show little changes over time and the changes of stocks—not the level of stocks—are relevant for the flow model, these strategic stocks of copper cathodes are neglected.

In contrast, there are no data on stocks of copper scrap and copper semis available. The use of high grade scrap—estimated from the difference between total annual semis production and copper cathode use—shows comparatively high volatility, particularly in recent years (see Figure S5).

Table S4: Mean average lifetimes and fabrication efficiencies. Both average lifetimes and fabrication efficiencies were estimated as follows: first, a starting value was extracted or derived from the existing literature (*8*, *11*, *13–15*); then, these values were cross-checked in a global survey of experts from the copper industry as well as from related organizations. Particularly in the case of fabrication efficiencies, the estimates from the industry were often lower than those from external observers. In case of dissent, the values used were those coming from the industry.

Field of use	End-use sector	Average lifetime in years	Fabrication efficiency
Building & Construction	Plumbing	40	0.95
	Building Plant	40	0.90
	Architecture	50	0.85
	Communications	30	0.90
	Electrical Power	40	0.90
Infrastructure	Telecommunications	30	0.90
	Power Utility	30	0.85
Industrial	Electrical Industrial	15	0.80
	Non Elec. Industrial	20	0.90
Transport	Electrical Automotive	12	0.75
	Non Elec. Automotive	15	0.90
	Other Transport	25	0.80
Consumer & Electronics	Consumer	8	0.75
	Cooling	10	0.80
	Electronic	5	0.75
	Diverse	10	0.75

There are various reasons for this observation, including the dependency of the availability of directly remeltable new scrap on the (volatile) semis production, the higher efficiency of scrap collection and separation in times of high copper prices and, notably, the existence of copper scrap stocks, whose magnitude depends on the prevailing price of copper. Because there is no data available regarding these temporary stocks of copper scrap, we chose to smooth the curve of directly melted scrap use (3-year average) and took this smoothed curve as the annual clean scrap availability. Thus, the difference between the smoothed curve of high grade scrap availability and the curve of annual directly meltable scrap use represents the changes in scrap stocks in the flow model (see Figure S5). By using this approach, it is possible to compensate for the build-up/depletion of scrap stocks—as far as these are reflected by the method outlined above—when calculating recycling indicators for each year.

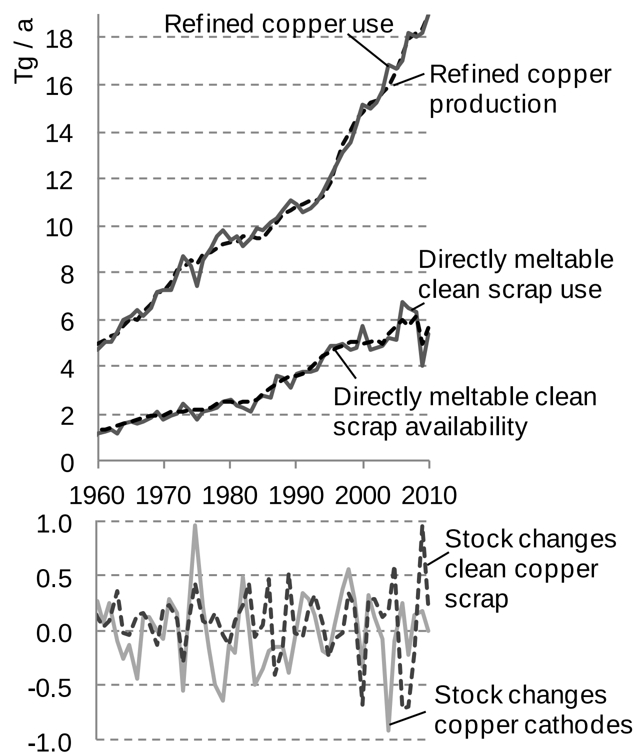


Figure S5: Annual copper cathode production, cathode use (*1*), directly remeltable scrap use and smoothed curve (three-year average used to map the annual clean scrap availability). Temporary stock changes derive from the difference between use and production/availability.

Stocks of copper semis were not included in the model. Although it is known that fabricators hold temporary stocks of semi finished goods, there is essentially no data available on these stocks. Furthermore, market experts (information derived from the global survey) estimate the level of the stocks themselves and especially their annual changes to be very small compared to the annual semis market. Finally, the existence of these stocks only minimally affects the copper recycling system—stock changes are distributed to final products and reach their end-of-life following different lifetime distributions. Thus, we believe that omission of these stocks does not negatively affect the results of the flow model.

Useful lifetime of final products

After incorporation into final products, copper enters the use phase, becomes part of the "stock in use" and remains there for the term of the useful lifetime of the products it is contained in. After this time delay, the final products (accounted for as copper content) are transferred to the waste management stage (described below). Stocks of copper for each market i at time t (denoted S_{it}) are estimated over time as

$$S_{it} = \sum_{t=t_0}^{t} (P_{it} - D_{it}) + S_{it_0} \tag{S1}$$

where P_{it} is the rate of production in market i at time t (input), D_{it} is the rate at which products in sector i leave the use phase and become available for postconsumer waste management (output), and S_{it_0} is the initial stock for market i, all expressed as contained copper. For illustration, a schematic of this approach is shown in Figure S6.

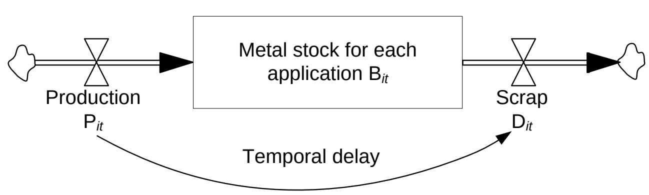


Figure S6: Methodology for accumulating stocks over time. B_{it} is the stock of copper in application/market i at any time t. This depends on the rate of production for market i at time t (P_{it}) and the rate at which these products (market i) are discarded at the same time t (D_{it}).

The initial values for stocks in use (B_{it_0}) of different copper end-use sectors were set such that the initial stocks equal the sum of initial waste streams for the first period of the average product lifetime ($\sum_{t_0}^{t_0+\text{average lifetime}} S_{it}$). Using this approach ensures that no initial stocks remain in use forever and prevents negative stocks. However, the model needs some time to stabilize until historical production data are reflected in the waste management section.

Values for P_{it} come from end-use datasets (see Table S1 and Supporting Information). Values for S_{it} are generated by applying a time delay to P_{it}. In the simplest case—that of fixed average lifetimes—this reduces to

$$S_{it} = P_{i(t-l)} \tag{S2}$$

where l is the average lifetime of products in market i. However, because the spread of age of discarded applications in waste streams is generally high (*16*), the use of lifetime distributions is considered a sensible approach. In this case, the values of available scrap for each market at time t can be estimated by

$$S_{it} = \sum_{l} P_{i(t-l)} h_l \tag{S3}$$

where the sum is calculated over all possible lifetimes l and h_l is the fraction of products in market i having lifetime l ($0 \leq h_l \leq 1$). In the field of quality and safety engineering, typical functions for lifetime distributions are the Weibull distribution, the Gaussian (normal) distribution, the log-normal distribution and the gamma distribution (see Figure S7) (*17*). However, on a global level, there is no empirical data for lifetime distributions available and the collection of such data is impractical. Therefore, assumptions for different average lifetimes were made based on the analysis of published regional data, and challenged through a global expert survey. The results of this process are shown in Table S4. The flow model uses Gaussian distributions with average lifetimes as expected values. Changes in the standard deviation have very low influence on the modeling results (see Figures S17 and S18). Although the model can allow for changing lifetime distributions over time, the values for h_l are kept constant due to lack of data and reasonable assumptions.

It is noteworthy that the amount and composition of the waste flow coming out of the use phase at time t do not equal the amount and composition of copper that entered the use phase at time t

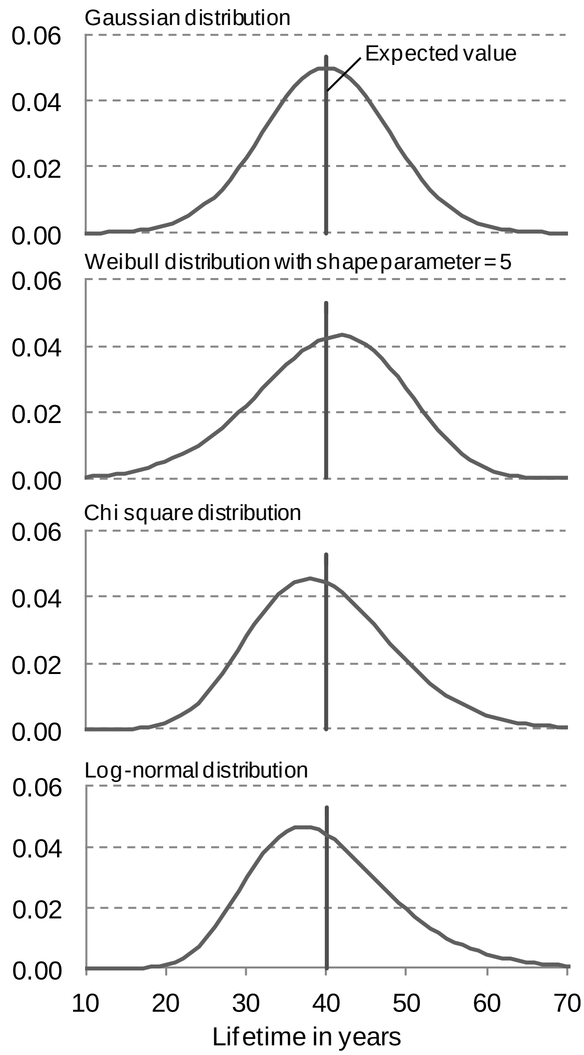


Figure S7: Typical lifetime-distributions in environmental and safety engineering (*17*). Note that the expected values are the same for all distributions and that the shape parameter of the Weibull distribution is set at 5 which gives this distribution a left skew (the tail of the distribution points to the left), whereas the Log-normal and the Chi^2 distributions are skewed to the right.

minus the weighted mean lifetime for all copper products. Instead, the amount of copper entering the waste management stage at time t is generally larger than that entering the use phase at time t minus the weighted mean lifetime for all copper products, with end-uses having comparatively short useful lifetimes (e.g. electronic applications) being overrepresented compared to their share at the time of entering the use phase. This is the result of the steadily increasing tonnage of copper used every year, as illustrated schematically in Figure S8.

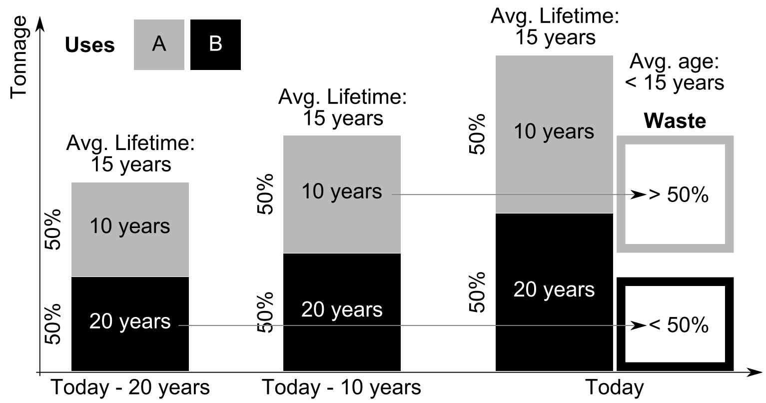


Figure S8: Differentiating between the average lifetime of copper in different end-use sectors and the average age of postconsumer copper flows in the global copper flow model. Note that this is a general example using two fictive applications A & B with lifetimes (in use) 10 & 20 years, respectively, intended to display the difference between the production an average lifetime ago and the current end-of-life material flows (difference between average lifetime of products and average age of EoL flows). This illustration does not refer to a specific year or specific sectors.

Waste management and recycling

After the end of its useful life, each product (accounted for as copper content) is transferred from the use phase to the waste management stage, where it is either collected for recycling or landfilled.

To guarantee the self-consistency of the metal flow model, a closed mass balance is required at every node and for every time step. In the following, we provide the derivation of the equation to calculate the collection rates of different scrap types to enable the conservation of mass over time. The IDs for fast identification of the flows in the equations refer to Figure S1 and Figure S12. Because both the total copper use as well as the production of primary copper are taken as given (input data), the tonnage of secondary metal for each year is calculated as

$$\text{Secondary copper} = \text{Total copper use [s]} - \text{Primary copper [a]} \tag{S4}$$

where the total copper use in a year is set to be equal to the fabrication of semi-finished goods.

The key variables/flows in the waste management stage are summarily sketched in Figure S9. These are either:

- directly generated by the model – new scrap of both high and low quality, available EoL scrap, secondary refined copper

- to be estimated – EoL scrap collected for recycling and, consequently, amount to be landfilled; EoL scrap both of high and low quality.

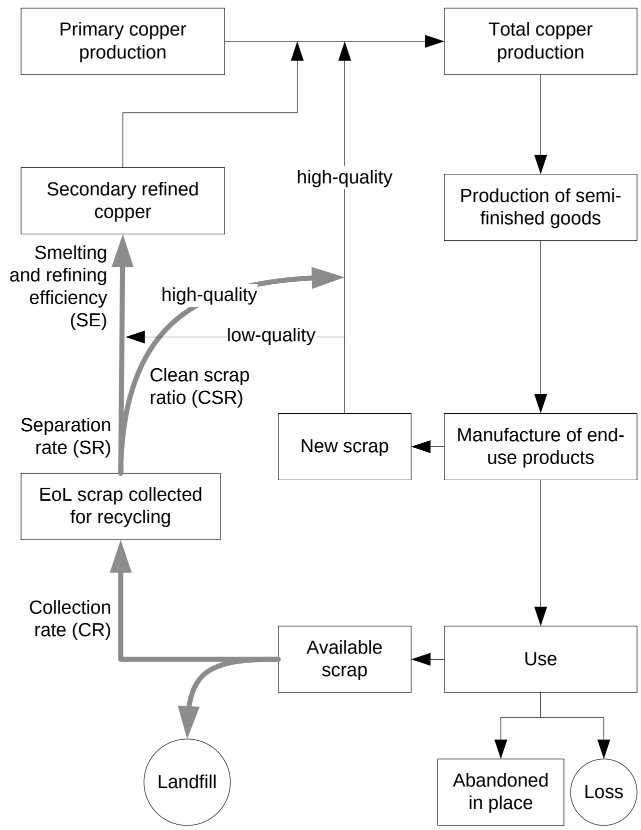


Figure S9: Key flows in the waste management and recycling process to be calculated from data and model output. Flows marked in gray are calculated in the model.

Taking the total metal use [s] (total fabrication of semi-finished goods) as a known variable (from production statistics), the flow coming from recycling (both new and old scrap) must equal the amount necessary to close the mass balance (cf. Equation S4). Though partly physically together, it is possible to separate the recycling of old and new scrap within the model. New scrap is generated in the manufacturing of final products and it is assumed that $\approx 90\%$ is directly remelted [k] while the other 10% [z] goes through smelting and refining (see "Manufacturing", above). Therefore, the estimation of recycled copper in the waste management stage is restricted to the estimation of flows coming from old scrap as follows:

$$\text{Recycled Cu from EoL scrap [i]} = \text{Total semis [s]} - \text{Mining [a]} - \text{New scrap [j]} \qquad \text{(S5)}$$

The amount of recycled copper from EoL scrap must satisfy two conditions (cf. Figures S1 and S9):

$$\text{Primary refined Cu [a]} + \text{Refined Cu from new and EoL scrap [r]} = \text{Total refined Cu [t]} \qquad \text{(S6)}$$

and

$$\text{Total refined Cu [t]} + \text{Direct melt Cu (from new scrap + EoL scrap) [l]} = \text{Total semis [s]} \qquad \text{(S7)}$$

where the only unknowns are refined and directly remelted copper from EoL scrap.

Examined at the next level of detail, the amount of directly remelted copper depends on the collection and separation rates of copper scrap as well as on the clean scrap ratio (high-grade copper scrap divided by the collected and separated total copper scrap). In addition to these, secondary refined copper also depends on the efficiency of smelting and refining.

There are significant differences between collecting and recycling copper from small consumer electronic devices compared to copper from cars and buildings or larger pieces of equipment. However, data concerning technical recycling efficiencies of copper from all 16 end-use sectors we considered in the model are not available. Therefore, copper leaving the use phase from the different sectors is assigned to one or more waste types in the flow model via the 'scrap matrix' provided in Table S5.

The following six different waste types which are a standard classification of postconsumer waste flows are taken into account:

1. Construction and demolition waste (C&D)

2. Municipal solid waste (MSW)

3. Electrical and electronic equipment waste (WEEE)

4. End of life vehicles (ELV)

5. Industrial electrical equipment waste (IEW)

6. Industrial non-electrical equipment waste (INEW).

Unfortunately, there is no empirical data available on a global basis which quantifies the amount of copper in different waste streams, though several regional studies contain estimates for copper in different waste fractions (*11*, *12*, *18*, *19*). Thus, the global accounting of waste streams is based on our own estimates/assumptions taking into account available regional data (*16*) and refined in the survey mentioned above. In addition to the six waste types, two further possible destinations are considered : dissipative loss and not collectable EoL products ("abandoned in place"). A detailed definition of these flows is provided in the stage "Environment" (below). Dissipative losses are accounted for at the end of the use phase even though these losses occur during the useful life of the products.

The treatment of the different waste types differs during waste management resulting in different technical efficiencies and recovery rates for copper. Data and assumptions concerning the processing efficiencies of copper for each waste fraction are given in Table S6. These figures were mainly extracted from literature on recycling processes and enhanced by survey input.

Thus, the extension of Equations S6 and S7 to account for different types of waste is

$$\text{Secondary Cu (EoL) [i]} = \underbrace{\sum_j \left(W_j CR_j SR_j CSR_j\right)}_{\text{from high-grade scrap [h]}} + \underbrace{\sum_j \left(W_j CR_j SR_j (1-CSR_j) SE_j\right)}_{\text{from low-grade scrap [r]}} \tag{S8}$$

where SE_j is the efficiency of smelting and refining for waste type j, W_j is the yearly amount of available waste of type j, and CR_j, SR_j and CSR_j are the corresponding collection rate, the separation/sorting/disassembling efficiency and the clean scrap ratio, respectively. While SE_j differs only slightly according to the type of scrap ($SE_j \approx SE$), CR_j, SR_j and CSR_j all vary depending on the

Table S5: Assigning different discarded products to different scrap types. Copper may also be lost to the environment (dissipation) or be abandoned in place and non-collectable for practical purposes (e.g. many subterranean cables). Although both of these (dissipation and abandonment) are potentially reversible copper losses, they are currently implemented as dead-ends. Notice that the table has 17 rows (instead of 16). The small market of copper powder from foundries (mainly for the chemical industry)—usually accounted for in "diverse products"—is listed separately. The reason for this is that, in contrast to other markets, the dissipative loss of copper in powder applications is set to 100% which means that no copper is recovered from these applications.

	Waste types							
	C&D	WSW	WEEE	ELV	IEW	INEW	Loss	Abandoned
Plumbing	0.95	-	-	-	-	-	0.01	0.04
Building Plant	0.95	-	-	-	-	-	0.01	0.04
Architecture	0.99	-	-	-	-	-	0.01	-
Communications	0.60	-	0.30	-	0.04	-	0.01	0.05
Electrical Power	0.79	-	0.20	-	-	-	0.01	-
Power Utility	0.49	-	0.10	-	0.40	-	0.01	-
Telecommunications	0.60	-	0.30	-	0.04	-	0.01	0.05
Electrical Industrial	-	-	0.10	-	0.89	-	0.01	-
Non Elec. Industrial	-	-	-	-	-	0.99	0.01	-
Electrical Automotive	-	-	0.10	0.89	-	-	0.01	-
Non Elec. Automotive	-	-	-	0.98	-	-	0.02	-
Other Transportation	-	-	0.09	0.80	0.10	-	0.01	-
Consumer	-	0.2	0.75	-	-	-	0.05	-
Cooling	-	-	0.79	-	0.20	-	0.01	-
Electronic	-	0.05	0.90	-	-	-	0.05	-
Diverse	-	0.20	0.55	0.10	0.05	-	0.10	-
Powder	-	-	-	-	-	-	1.00	-

Table S6: Technical efficiencies of the recycling process for different scrap types. These efficiencies were taken from regional studies on copper recycling (*11*, *12*, *20–22*) and cross checked by technical literature (*15*, *23–25*) and a global research project on copper recycling (*16*) and finally refined during our survey with experts from copper institutes and copper industry. However, we had to estimate global average values which is very challenging as technical aspects of waste management and recycling strongly differ from region to region particularly when comparing developing and developed countries. Therefore, the global separation efficiencies are slightly lower than in most regional studies)

Waste type	Separating, sorting, disassembling efficiency (SR_j)	Scrap smelting & refining efficiency (SE_j)
C&D	0.90	0.99
WEEE	0.55	0.97
ELV	0.55	0.97
IEW	0.70	0.97
INEW	0.75	0.99
MSW	0.20	0.97

discarded product to be recycled (grouped as waste types) as well as with time. The left hand side of Equation S8 is derived from the mass balances above, while W_j is provided by the model and SE_j can be assumed. There remain, therefore, three unknowns for each scrap type in Equation S8: CR_j, SR_j and CSR_j. Thus, by assuming a mean value for any of the three, the average values for the remaining two may be calculated because the value of each right hand term in Equation S8 is known (solution to Equations S6 and S7) providing two independent equations. Notice that the values for SR_j shown in Table S6 cannot be used directly to estimate a weighted average of the different SR_j values, because the weights depend on the collection rate (CR_j). Furthermore, because of the large differences in the efficiency of recovering copper from different EoL products (cf. Table S6), it is not desirable to estimate only an overall collection rate by assuming a single value of processing efficiency. To go beyond this level of detail, however, it becomes necessary to generate estimates for the collection rate for each type of waste (CR_j), combine these with the corresponding efficiencies of copper recovery from each product/waste type (SR_j and SE_j, from Table S6), take into consideration the clean scrap ratio (CSR_j), and check that the resulting amount of recycled copper yields a closed mass balance.

Generating estimates for CR_j and CSR_j for each waste type is not possible analytically on the basis of the available data. Therefore, we devised a calculation method which provides these estimates based on expert input and values generated within the global flow model (new scrap, available old scrap), assumptions on the distribution of scrap to different scrap types (see Table S5) and the corresponding recycling efficiencies (Table S6). The higher level of detail in the recycling part of the model results in a higher complexity for the calculation of collection rates and high-grade scrap fractions. However, the basic methodology remains equal to the system described above (cf. Figure S9). The calculation method of the waste management and recycling part of the model is explained in Figure S10, using a system with 3 different EoL applications and 2 different scrap types as an example.

Equation S8 continues to be valid in Figure S10. However, for the following calculations it is necessary to substitute CR_j by an auxiliary collection rate aCR and a factor, f_{CR_j}, defining the relationship between different CR_j as follows:

$$CR_j = f_{CR_j} \cdot aCR \tag{S9}$$

where $f_{CR_j} \cdot aCR < 1 \; \forall \; f_{CR_j}$ and aCR is calculated at each time step to close the mass balance as described below.

Following the path of high-grade scrap (clean scrap) in Figure S10, we arrive at

$$\text{High-grade scrap for direct melt [h]} = \sum_j \left(W_j CR_j SR_j CSR_j \right) \tag{S10}$$

with two unknowns: CR_j and CSR_j. By substituting $CSR_j = f_{CSR_j} \cdot aCSR$ (analogous to CR_j) into Equation S10, we can solve this for $aCSR$ in terms of CR_j (and consequently aCR) through Equation S9). We then substitute the resulting $aCSR = f(f_{CSR_j},\, f_{CR_j},\, aCR)$ into Equation S8 and

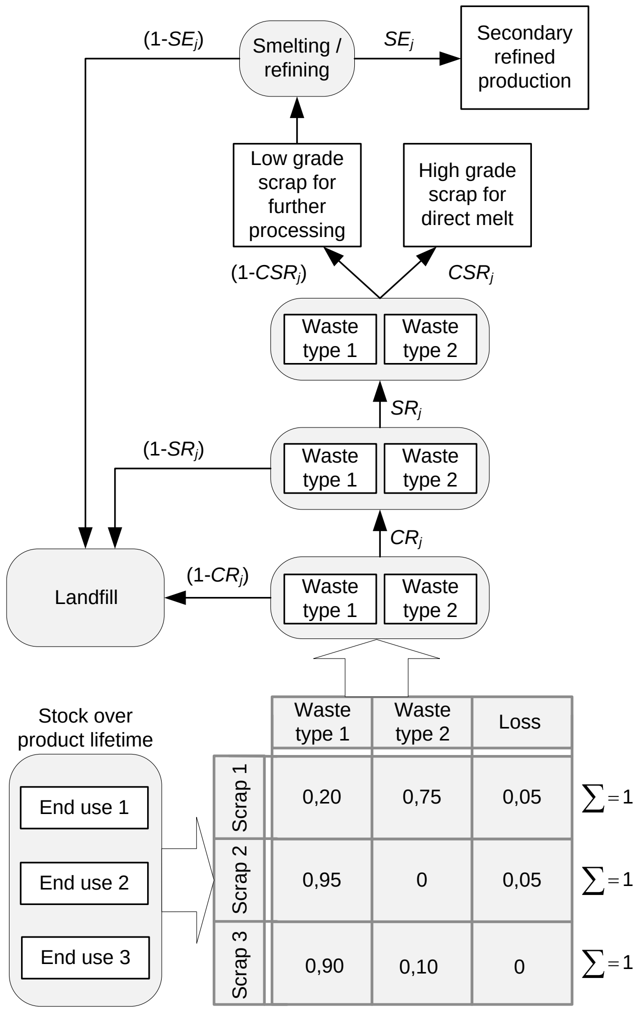


Figure S10: Graphical overview of the accounting and calculation methodology within the waste management and recycling section of the model

solve this for $aCR = f(f_{CSR_j}, \ f_{CR_j})$.

$$aCR = \frac{\text{Secondary Cu (EoL) [i]} - \left(\text{High-grade scrap [h]} \cdot \sum_j \left(\frac{W_j f_{CR_j} SR_j (1 - SE_j)}{\sum_j \left(W_j f_{CR_j} SR_j f_{CSR_j} \right)} \right) \right)}{\sum_j \left(W_j f_{CR_j} SR_j SE_j \right)} \qquad \text{(S11)}$$

In Equation S11, the value for total “Secondary Cu (EoL)” is calculated from Equation S5 while the “high-grade scrap” for direct melt results from Equation S7 based on historical figures. A graphical summary of this calculation method is provided in Figure S11.

The factors f_{CSR_j} and f_{CR_j} (both fulfilling the condition $f_{CR_j} \cdot aCR < 1$ and $f_{CSR_j} \cdot aCSR < 1$), are then chosen by trial and error such that the resulting relationship between different collection rates and clean scrap ratios are in line with reasonable assumptions derived from literature (*15*, *23*, *24*) and cross-checked in the survey (e.g. the collection rate for copper recycling in end-of-life vehicles is much higher than that for copper recycling in municipal solid waste). Notice that this approach has the key advantage of insuring a closed mass balance. This makes it impossible to adjust single values without affecting the remaining estimates: e.g. if the resulting collection rate for one waste type appears too low, it can be increased (by increasing f_{CR_j}) but this adjustment will result in a commensurate decrease in the collection rate for all other waste types. The same applies to the clean scrap ratio.

Also noteworthy is that values of both the collection rate and the clean scrap ratio are calculated at every time step and, therefore, may vary from year to year in the model. This arises within the model as a consequence of maintaining a closed mass balance every year. In reality, those variations may be observed due to changes in price, technology and availability and composition of scrap. Furthermore, the separation rate (SR_j)—kept constant in the model—is also known to vary for the same reasons. Therefore, the year-to-year variability in SR_j is included in the variability of CR_j and CSR_j (convolution).

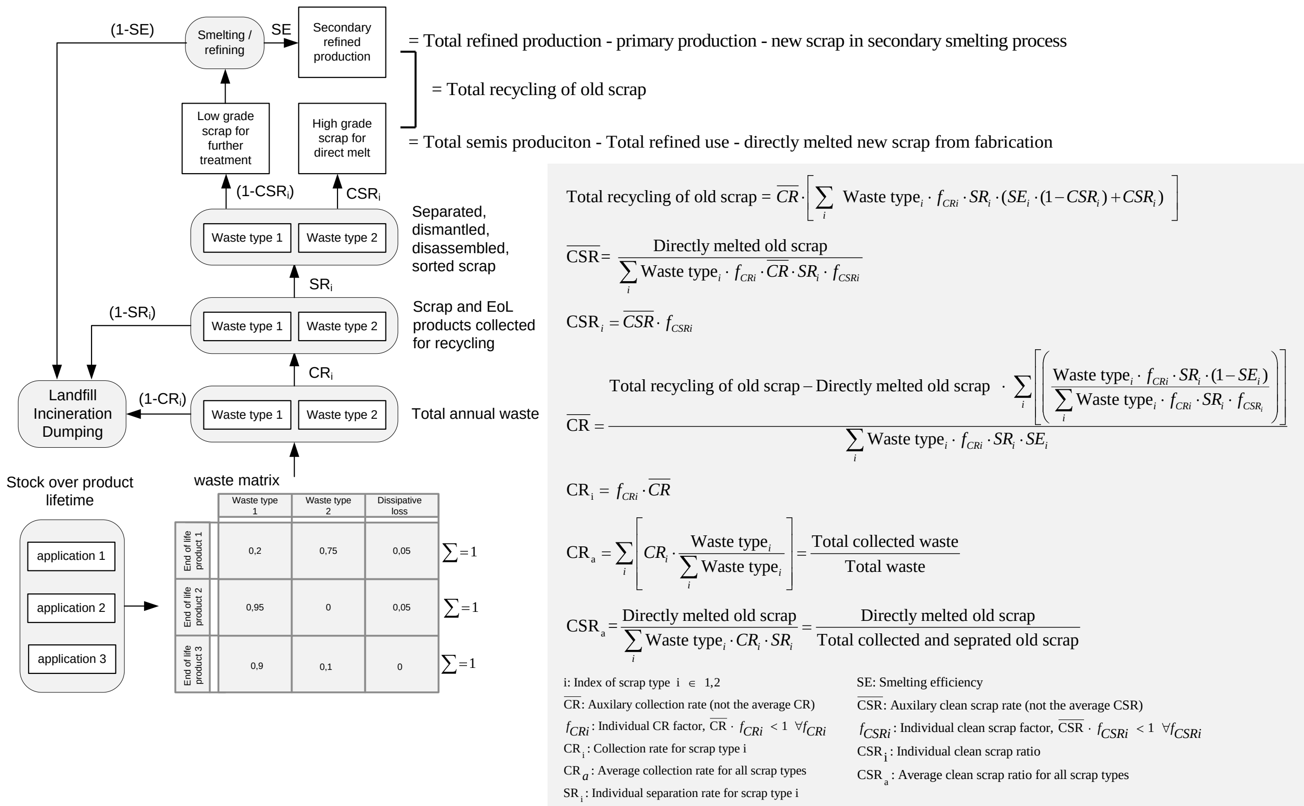


Figure S11: Summary of the calculation method for the End-of-Life Collection Rates

Environment

The environment stage is both the source and eventually the sink for all copper in the model. As a source, no limits are imposed on the yearly amount of copper mined (input to the model is the yearly primary copper production). As a sink, emissions to the environment are included only insofar as they contain copper. Two types of emissions/losses are included in the model:

1. Irreversible losses (dissipation), and

2. Potentially reversible losses: landfills and material abandoned in place (accounted for separately)

with all stocks and flows accounted for on the basis of their copper content.

Dissipative losses occur mainly during the use phase of copper applications due to corrosion and abrasion and are accounted for in their entirety on a market-by-market basis at the time products leave the use phase. Some of the dissipated copper will become part of sewage sludge and might be reused as a fertilizer (*26*). However, as copper is not recycled from this flow, sewage sludge and its copper content are treated as irreversible losses in the model and are not included in the waste management stage (see above).

A comparable loss of copper to the environment occurs during waste incineration—currently mainly used for the treatment of municipal solid waste (MSW) in industrialized countries—leading to about 90% of the copper content being lost to bottom ashes (*12*) from which copper is normally not recovered (*27*). If not landfilled, these ashes are sometimes used as road base materials and for foundations of buildings (*28*, *29*). However, these copper flows are comparatively small and, because copper is not recovered (*30*), are not considered as recycling in this work. Available scrap not collected for recycling is, if not incinerated, dissipated or abandoned in place, automatically assigned to the landfill stock (see "waste management", above).

The "abandoned in place" stock refers to copper applications mainly from the field of building and construction which may remain in place after their use phase and are not available for waste management and collection. This relates e.g. to copper in underground cables, tubes or communication and electric cables in buildings which may not be removed after the installation of new infrastructures. The "abandoned in place" stock is not directly comparable to EoL copper products which have been summarized under the term of "hibernating" copper in previous studies (*31*). In the model, we attempt to take into account the fact that different products are kept in attics, cellars, basements or factory halls for several years (hibernating) by implementing broad lifetime distributions of different products. Thus, this temporary stock of copper is treated as a life-time extension. However, the "abandoned in place" stock (which is relatively small and does not have a strong impact on the modeling results) remains in place over the whole modeling time, analogous to dissipated copper, even though theoretically it could be a source for recycling.

Slags and residues from smelting, refining and mechanical waste treatment, from which copper is not economically recyclable, are accounted to landfills as well. Tailings and gangue from copper mining, leaching and milling, which represent large amounts of copper emissions to the environment (see "primary copper production", above) are not regarded as landfilled copper in the context of waste management and are accounted for separately. Copper lost to other recycling loops during scrap treatment (mainly to steel and in smaller amounts to aluminum recycling) is accounted for separately on the basis of data from regional copper models (*11*, *18*, *31*).

Summary evaluation of the model

The global model of copper flows described here is flexible, dynamic and self-consistent. Considerable effort was invested in making it an extension and not a replication of models already developed and described in the literature. In particular, it covers global (not regional) copper flows over several decades (not one base year) and may be used to estimate values for various recycling indicators. Through access to all model flows and the transparency in both data basis and assumptions, it is possible to evaluate the resulting recycling indicators in terms of their robustness. The self-consistency of the model guarantees that the consequences of changing individual assumptions become clear.

Although particular attention was given to collecting the best available data, all uncertainties tied to that data are also transmitted into the model. Furthermore, a number of assumptions (including extrapolation of country and regional data to the regional and global level) were required to compute material flows within the model. These assumptions were cross-checked in a global survey of copper experts both from the copper industry and related organizations. However, there is a need to successively validate these assumptions and replace them with empirical data where possible.

The model is capable of depicting changing conditions with time both directly (e.g. changing market structure, lifetime distributions, technical recycling efficiencies) and indirectly (e.g. increased disassembly efforts in times of high copper prices through the separation/sorting/disassembling efficiency). Unfortunately, this capability is not yet fully used because of lack of the required data but can be exploited as soon as reasonable estimates become available.

Definition of recycling indicators

The majority of the eight recycling indicators used in this work has been defined by EuroMetaux (European Association of Metals) (*32*) and UNEP (United Nations Environment Programme) (*33*) and was applied to several static metal cycles in previous studies (*11*, *12*, *34*, *35*). However, we included some indicators which have been less used in the past such as the End-of-Life Recycling Input Rate (EoL RIR) or the Old Scrap Ratio (OSR) which enables a clear distinction between recycling of old scrap (from EoL products) and total recycling including new and old scrap. The set of indicators used is as follows (see Figure S12):

1. Recycling Input Rate (RIR): The RIR measures the proportion of metal and metal products that are produced from scrap and other metal-bearing low-grade residues (both old and new scrap).

2. End-of-Life Recycling Input Rate (EoL RIR): The EoL RIR measures the proportion of metal and metal products that are produced from EoL scrap and other metal-bearing low-grade residues (only EoL scrap).

3. Overall Recycling Efficiency Rate (Overall RER): The Overall RER indicates the efficiency with which end-of-life scrap, new scrap and other metal bearing residues are collected and recycled.

4. End of Life Recycling (Efficiency) Rate (EoL RR): The EoL RR indicates the efficiency with which EoL scrap is recycled. It is an indicator for the waste management and recycling system performance.

5. Overall Processing Rate (Overall PR): The Overall PR (also called Overall Recycling Process Efficiency Rate) measures the efficiency with which the metal products are recovered from the collected scrap (both old and new scrap).

6. End of Life Processing Rate (EoL PR): The EoL PR (also called EoL Recycling Process Efficiency Rate) measures the efficiency with which the metal products are recovered from

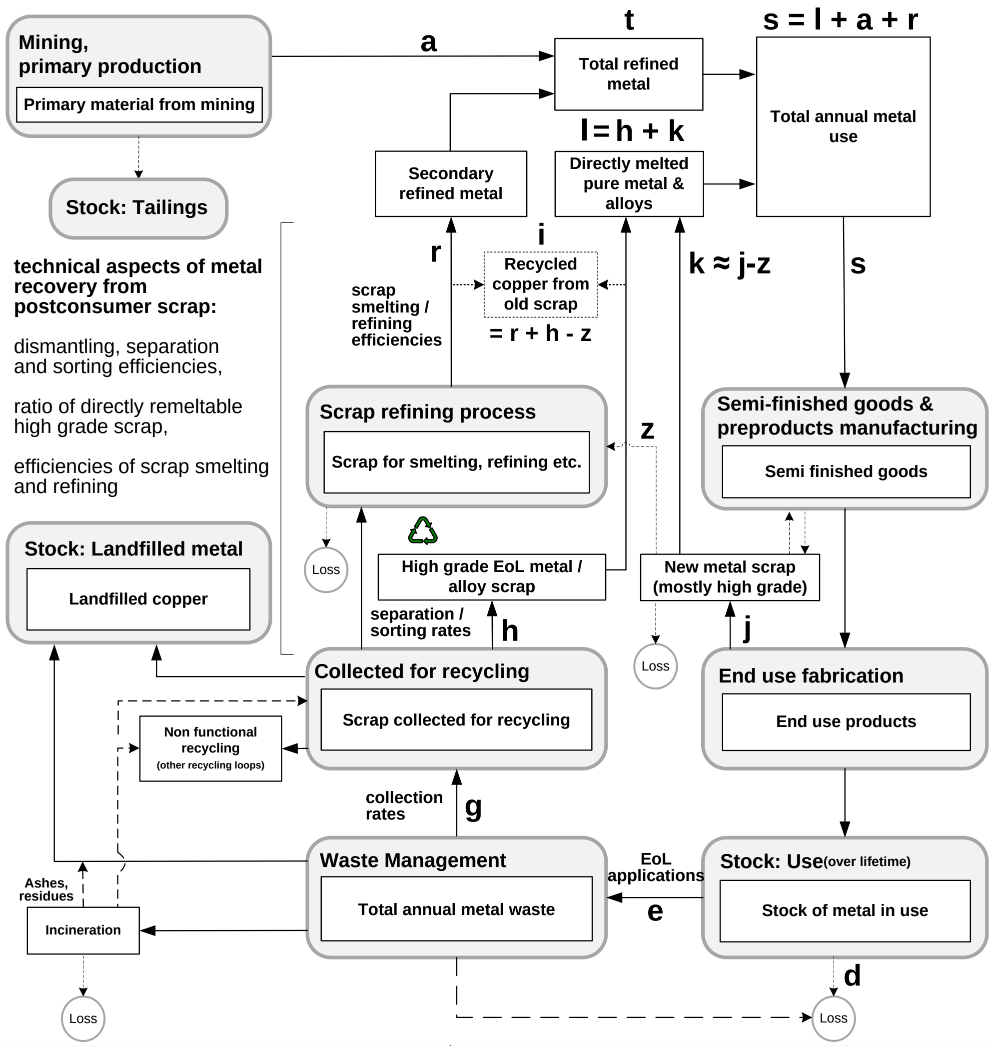
the collected EoL scrap. It is an indicator for the performance of the technical EoL recycling process.

7. End of Life Collection Rate (EoL CR): The EoL CR measures the efficiency with which EoL scrap is actually collected for recycling.

8. Old Scrap Ratio (OSR): The OSR measures the percentage of recycled metal from old scrap within the total secondary metal use from new and old scrap.

Note that the similarity in the definition of recycling indicators leads to a strong correlation in their values over time. For example, the total amount of annual copper waste is in the denominator of the EoL RR and the EoL CR and also part of the definition of the overall RER. Furthermore, the year-to-year variations in mining, refined copper and semis production directly affect the different indicators in the same way. The exception to this is the EoL PR, which basically arises from the technical efficiencies along the recycling process chain and depends only minimally on collection rates and production figures. However, not only the total amount but also the composition (distribution by end-use) of copper and alloy waste is important because different products are recycled with different efficiencies.

The end-of-life collection rate is defined as the ratio of scrap collected with the intention to recover copper. This does not mean that waste fractions not collected for copper recycling will remain in place—but they are dumped, landfilled, incinerated or further treated without recovering copper. It has to be considered that in all these fractions, copper usually occurs within a mix of different kinds of organic (mainly plastics) and inorganic (metals & minerals) materials wich affects both the collection and particularly the separation of copper. The recycling of EoL vehicles is an established industry all over the world. This is the reason for the relatively high collection rate of ELV. However, the main intention of car recycling is the recovery of steel and in smaller amounts aluminium. As copper only forms a byproduct of the process, the efficiency of copper separation from collected scrap is comparatively low because much material is lost to other material fractions. The opposite is true for copper within construction & demolition waste. The effort of collecting copper wires, tubes etc. from rubble of deconstruction activities is very high and—once the copper scrap is collected—the separation and recovery of copper is feasible with very high efficiencies.



Recycling Input Rate (RIR) **= (r+l) / s**	End of Life Recycling Input Rate (EoL RIR) = i / s = RIR • OSR
End of Life Recycling Rate (EoL RR) **= i / e = EoL PR • EoL CR**	Overall Recycling Efficiency Rate (Overall RER) = (r+l) / (e+j)
Old Scrap Ratio (OSR) **= i / (r+l)**	Overall Processing Rate (Overall PR) = (r+l) / (g+j)
End of Life Collection Rate (EoL CR) = g / e	End of Life Processing Rate (EoL PR) = i / g

Figure S12: Calculation of selected recycling indicators based on model results.

Additional results

Aggregated global copper flows

Figures S13, S14 and S15 provide the simulation results for the base year 2010 and for the aggregated period 2000-2010 in form of simplified form.

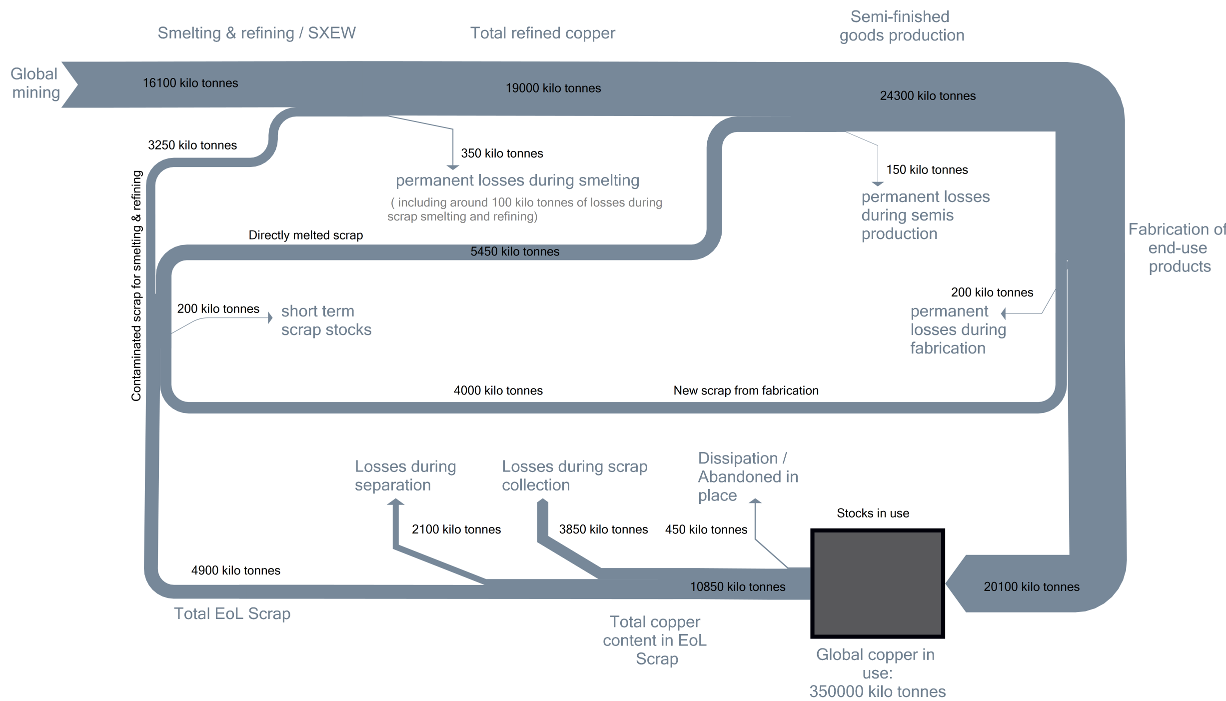


Figure S13: Sankey diagram of all aggregated flows in the model for the base year 2010. Permanent losses do not directly refer to the average process efficiency but take into account the copper which is recovered from slags and copper containing solvents. The postconsumer recycling flow of 4.9 Tg does not yet include further losses during smelting and refining of around 0.1 Tg (cf. Figure S14).

Sensitivity analysis and uncertainty evaluation

As discussed in the corresponding paper we first analyzed the effects of changes in shape and changes of the expected values of the lifetime distributions on the calculated recycling indicators. The results are listed below.

Further results from the stochastic sensitivity analysis are presented below.

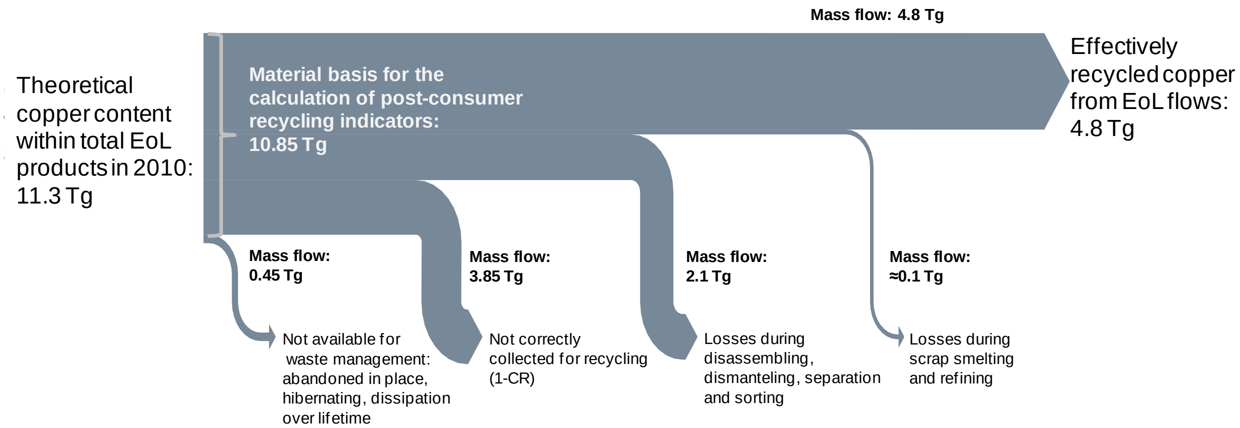


Figure S14: Mass flows within the waste management system for one base year (2010). Note that this sankey diagram only refers to "functional" recycling of copper. Losses to other recycling loops (steel, aluminium, incineration ashes) where copper might remain in form of impurities are considered as losses.

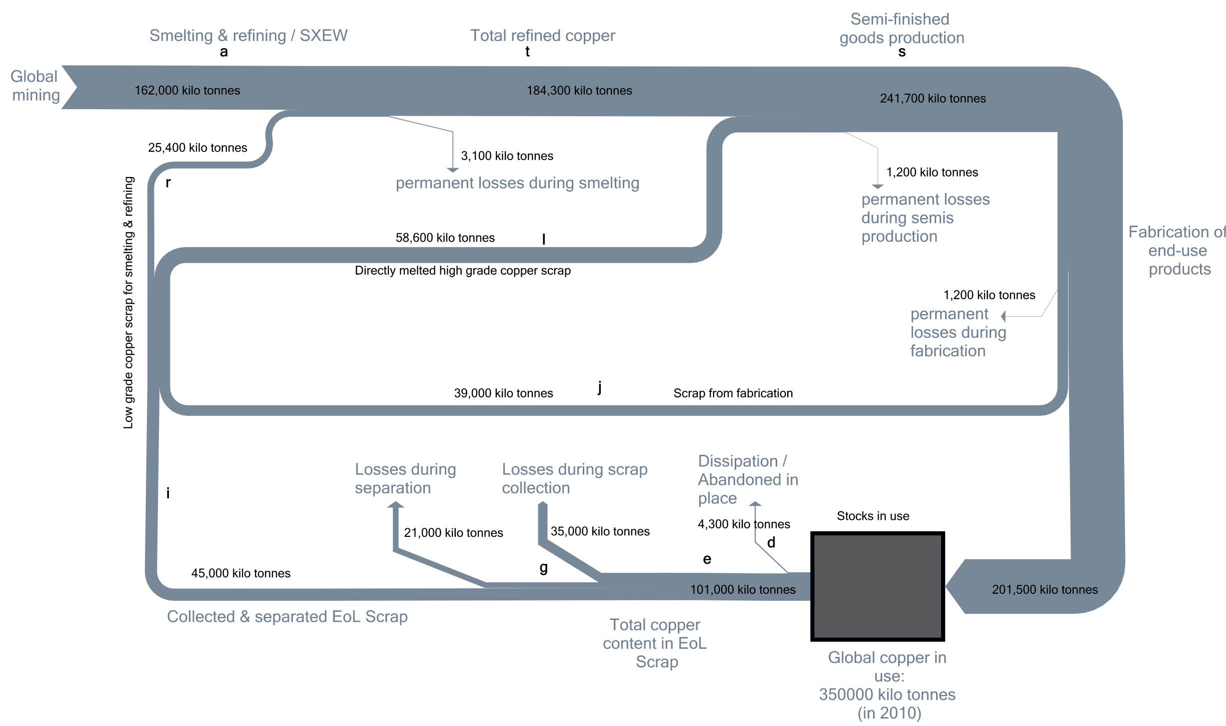


Figure S15: Sankey diagram of all aggregated flows in the model for the period 2000-2010

Table S7: Average values and standard deviations of the calculated global recycling indicators considering both year-to-year changes and the uncertainty introduced by the underlying assumptions (lifetimes and fabrication efficiencies).

Indicator	Mean	Standard deviation
RIR	0.35	0.02
EoL RIR	0.19	0.03
Overall RER	0.61	0.04
EoL RR	0.45	0.05
Overall PR	0.80	0.01
EoL PR	0.68	0.01
EoL CR	0.66	0.07
OSR	0.54	0.05

Table S8: Estimated recycling rates at the level of applications. Note that the seperation efficiencies and the technical recycling process efficiencies for the model were estimated on the basis of waste types, not on the basis of EoL products. The figures shown in this table are a result of calculating backwards, taking into account the allocation of different EoL products to the waste types (cf. corresponding paper). See the main text for a brief discussion on the limitations of these values. The values refer to the period 2000-2010.

Waste type	EOL Collection Rate	deviation over time	EOL Recycling Rate	deviation over time	EOL Recycling Processing Rate	deviation over time
Plumbing	0.687	0.058	0.615	0.052	0.850	0.001
Architecture	0.716	0.061	0.641	0.054	0.886	0.002
Building Plant	0.687	0.058	0.615	0.052	0.850	0.001
Communication	0.648	0.055	0.508	0.043	0.727	0.001
Electrical Power	0.696	0.059	0.579	0.049	0.816	0.001
Power Utility	0.682	0.057	0.534	0.045	0.770	0.001
Telecommunication	0.648	0.055	0.508	0.043	0.727	0.001
Elect. Industrial	0.653	0.058	0.442	0.039	0.670	0.001
Non Elect. Industrial	0.673	0.062	0.500	0.046	0.736	0.001
Elect. Automot.	0.904	0.044	0.490	0.024	0.537	0.000
Non Elect. Automot.	0.904	0.044	0.490	0.024	0.537	0.000
Other Transport	0.828	0.045	0.469	0.026	0.567	0.000
Consumer	0.478	0.045	0.256	0.024	0.446	0.000
Cooling	0.637	0.057	0.394	0.035	0.610	0.001
Electronic	0.565	0.052	0.305	0.028	0.498	0.000
Diverse	0.478	0.040	0.261	0.021	0.426	0.000

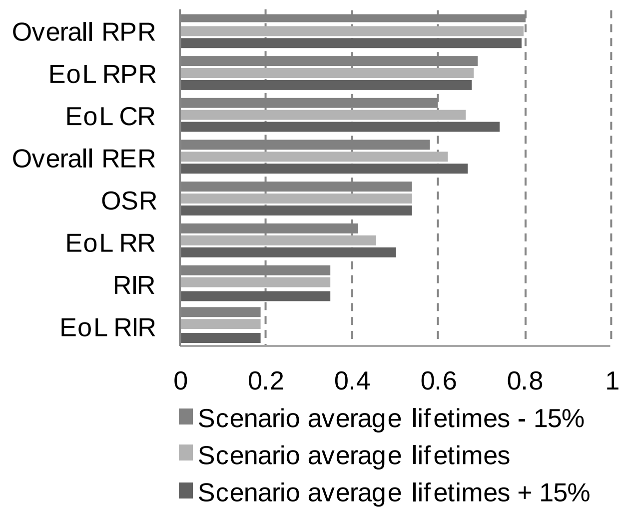


Figure S16: Effect of changes of average lifetimes on the calculated recycling indicators. The values refer to the period 2000-2010.

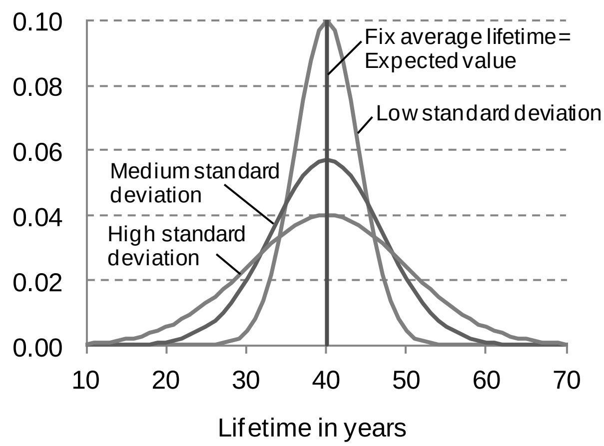
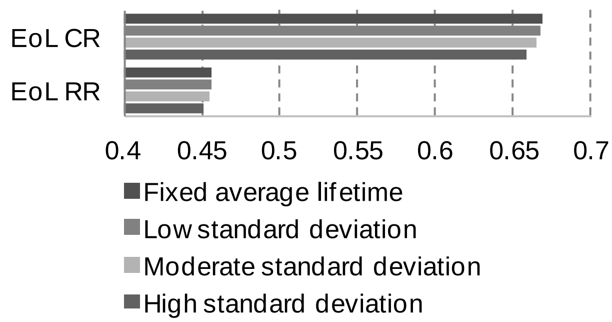
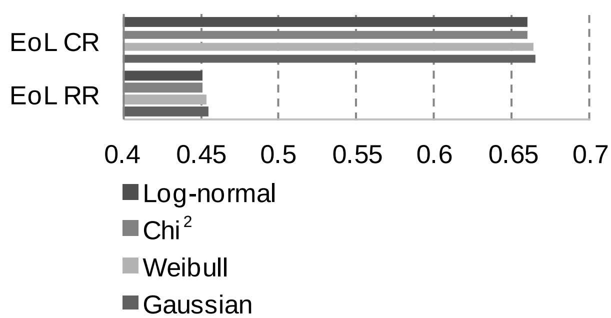


Figure S17: Different levels of the standard deviation for Gaussian ditributions. In the "low" case all standard deviations were set to 10% of the expected value, in the "moderate" case 17.5% and in the "high" case 25%.



(a) Effect of changes in the standard deviation of the Gaussian distributions. In the "low" case all standard deviations were set to 10% of the expected value, in the "moderate" case 17.5% and in the "high" case 25%. The case of fixed average lifetimes may be interpreted as a Gaussian distribution with a deviation of 0 (see Figure S17).



(b) Effect of functional changes of lifetime distributions on the calculated recycling indicators. Note that the expected values are the same for all distributions and that the shape parameter of all Weibull distributions is set at 5 which gives these distributions a left skew (the tail of the distribution points to the left), whereas the Log-normal and the Chi^2 distributions are skewed to the right (see Figure S7).

Figure S18: Effect of changes in the shape of the assumed lifetime distributions on the calculated recycling indicators. The values refer to the period 2000-2010.

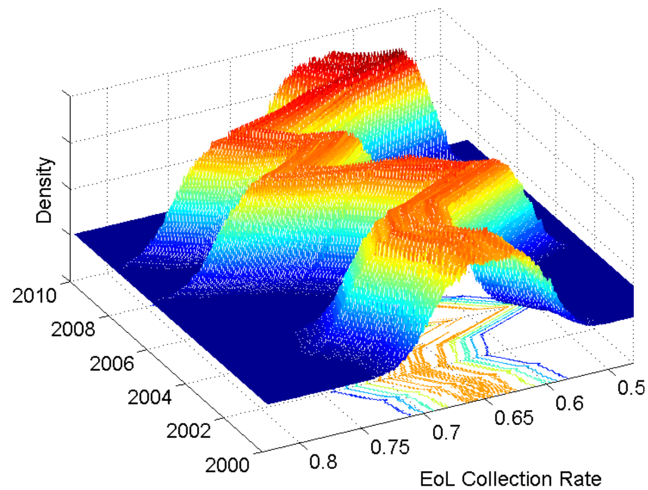


Figure S19: Result of the stochastic simulation for the EoL collection rate: A close to normal distributed function over the timeline.

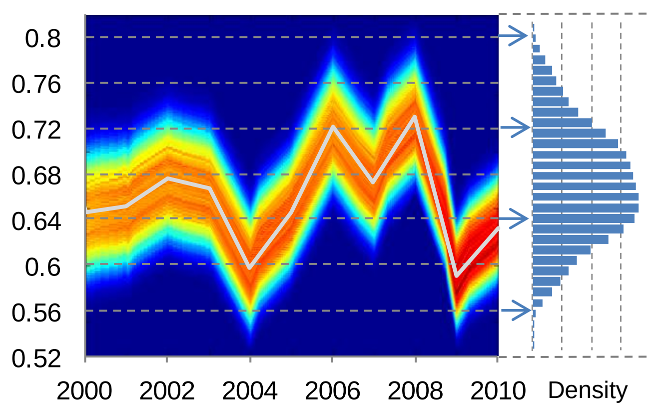


Figure S20: Extraction of the average density function on the example of the EoL CR. Both the spread over time and the spread caused by uncertainty are taken into account. The function in the middle shows the modeling results with average values as the "best choice".

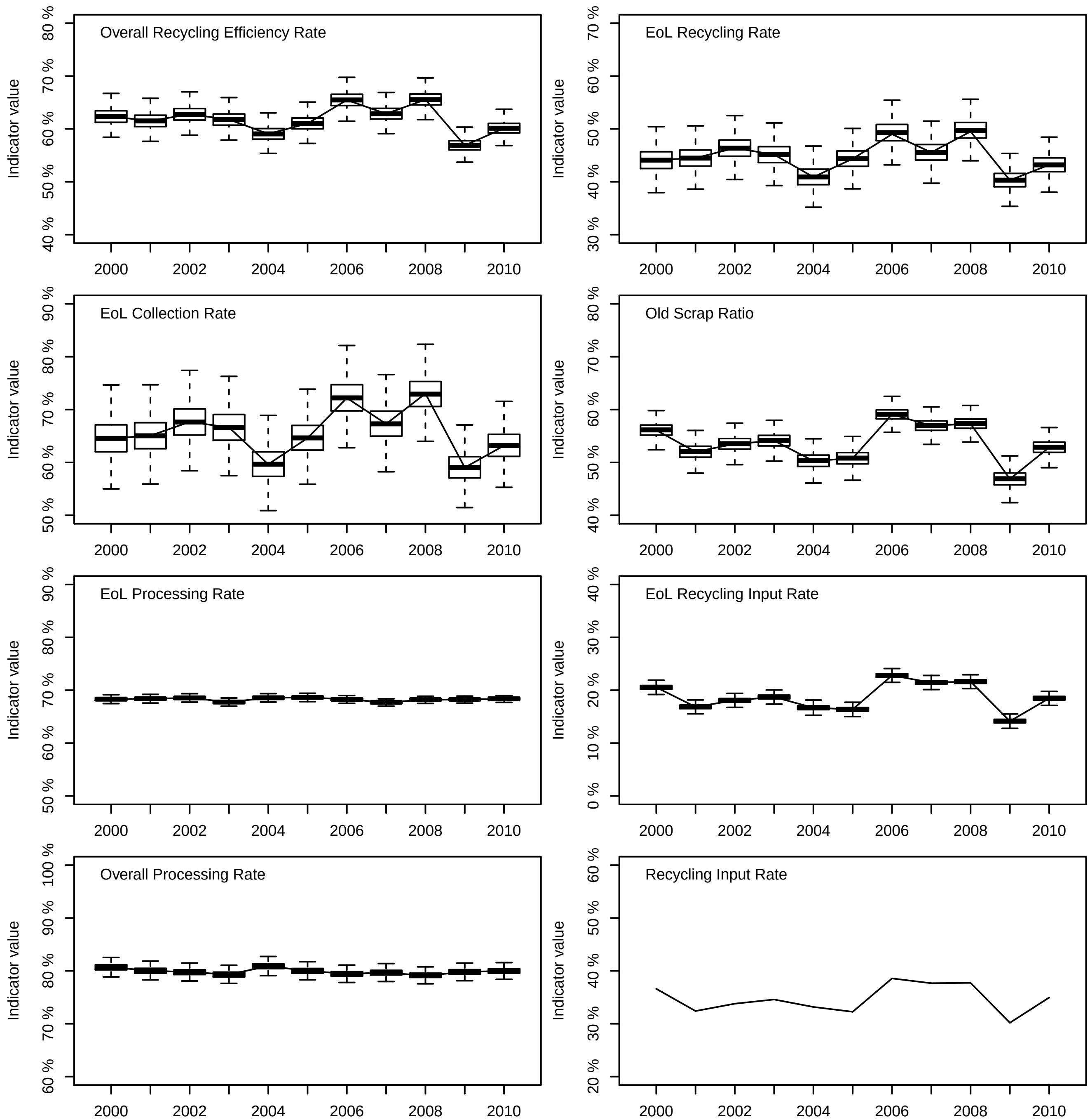


Figure S21: Boxplot of the results of the stochastic simulation for all indicators. Note that the Recycling Input Rate (RIR) only depends on global mining and production data and was therefore not affected by the stochastic sensitivity analysis.

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