Environmental Science & Technology

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Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation

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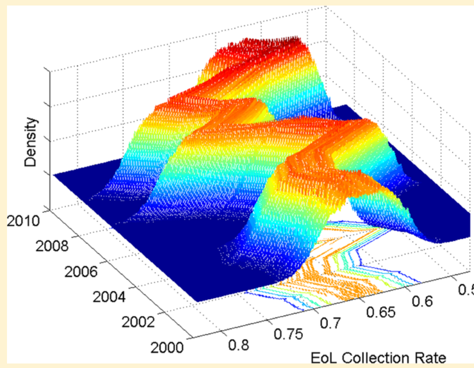
Supporting Information

ABSTRACT: We present a dynamic model of global copper stocks and flows which allows a detailed analysis of recycling efficiencies, copper stocks in use, and dissipated and landfilled copper. The model is based on historical mining and refined copper production data (1910−2010) enhanced by a unique data set of recent global semifinished goods production and copper end-use sectors provided by the copper industry. To enable the consistency of the simulated copper life cycle in terms of a closed mass balance, particularly the matching of recycled metal flows to reported historical annual production data, a method was developed to estimate the yearly global collection rates of end-of-life (postconsumer) scrap. Based on this method, we provide estimates of 8 different recycling indicators over time. The main indicator for the efficiency of global copper recycling from end-of-life (EoL) scrap—the EoL recycling rate—was estimated to be 45% on average, ± 5% (one standard deviation) due to uncertainty and variability over time in the period 2000−2010. As uncertainties of specific input data—mainly concerning assumptions on end-use lifetimes and their distribution—are high, a sensitivity analysis with regard to the effect of uncertainties in the input data on the calculated recycling indicators was performed. The sensitivity analysis included a stochastic (Monte Carlo) uncertainty evaluation with 10^5 simulation runs.



■ INTRODUCTION

Material flow analysis (MFA) is a common analytical tool to characterize material stocks and flows within national, regional, and global boundaries. While MFA may address composite flows of numerous materials, the term substance flow analysis (SFA) is utilized when referring to specific substances such as copper.[1] SFA helps to quantify where metals are introduced into economies, where they are used and stored, discarded, and recycled or where they dissipate into the environment.

Due to its properties, such as its thermal and electrical conductivity or its resistance to corrosion, copper has become a major industrial metal, ranking third after iron and aluminum in terms of quantities consumed.[2] Currently, on the order of 25 Tg (million metric tons) of copper are used worldwide to produce a wide variety of copper and copper alloy products (global fabrication of semifinished goods in 2011 including all primary and secondary copper use). On account of its extensive use and its price level, there are both compelling economic and environmental reasons for recycling copper. In fact, approximately one-third of global demand is estimated to be covered through recycling of new and old scrap.[3]

Despite the importance of copper to the functioning of modern economies, there is currently no dynamic material flow model for copper at the global level.[4] Most existing models are of regional character or are static analyses exploring copper flows for one base year.[5−15] There are several dynamic flow models on a regional basis, mainly focusing on the estimation of copper stocks in use.[1,16,17] On a global scale, Eckelman and Daigo[18] analyzed the copper life cycle through Markov Chains based on static state transition tables from the year 2000, and Graedel et al.[19] presented a detailed static model of global copper flows for the year 1994. Furthermore, Gerst[20] presented a detailed estimation of current and future copper stocks on a regional and global level, following a bottom-up approach based on scenarios for the use of copper containing technologies and assumptions of their metal content. In 2003, Ayres et al.[21] presented a detailed life cycle assessment of copper and its byproducts lead and zinc including a forecasting model for copper demand. However, these models do not reflect current reality because they either do not sufficiently cover all life-stages of copper (especially waste management and recycling) or they refer to outdated figures. In particular, the demand for industrial metallic raw materials increased strongly in the past 15 years, largely due to the rapid growth of the BRIC economies and their high investments in electric and other infrastructures.[22] Thus, there is a need for both an update of the flow models with current data and for a switch from a static to a dynamic modeling approach in order to reach a

Received: January 9, 2013
Revised: May 8, 2013
Accepted: May 13, 2013
Published: May 13, 2013

better understanding of the system as a whole, reflecting trends in mining, production, use, and recycling of copper—in particular, how much copper is recycled compared to the amount of available copper scrap? We aimed to provide such estimates through the development and use of a dynamic model of global copper flows which simulates mass flows over time from mining, production of copper cathodes, fabrication of semifinished and end-use goods, stocks over product lifespan to waste management, and recycling of endof-life scrap (postconsumer scrap). Furthermore, we report on the use of this model to estimate a number of key recycling indicators.

■ METHODS

The model described herein corresponds to an open metal cycle because considerable amounts of postconsumer material flows are lost, e.g., to landfills.[23] In general, stock-and-flow models are all open cycles, with the exception of a study on steel where a perfectly closed cycle was assumed.[24] An important contribution of the model presented in the following is the method for calculating the collection efficiency of postconsumer material flows in dependency of yearly reported production data, making it possible to provide detailed information of current recycling efficiencies by following each sectoral EoL flow separately and taking into account technical aspects of scrap treatment. By comparison, other dynamic top-down models for aluminum and copper on a regional level have closed the mass balance by aggregating all EoL flows[1,15] thereby losing information of recovery efficiencies from specific EoL flows and waste fractions, or by assuming a perfectly closed loop regarding scrap collection, as in the case of steel.[24]

Copper Flow Model. A detailed description of the model underlying this work, including the input data and data sources, a derivation of all relevant equations and further information of the survey work relating to this project can be found in in the Supporting Information. Briefly, we used a top-down modeling approach to simulate global copper stocks and flows and to give a detailed insight into the state-of-the-art or current recycling efficiencies.

The global copper flow model comprises five conceptual "life stages": primary production, manufacturing, use, waste management, and environment. The model essentially follows each ton of copper coming from primary production through to the manufacturing of final products. After manufacturing (we considered 17 different end-use sectors), the copper contained in these products enters a use phase and remains there for different periods of time depending on the product lifetime. After leaving the use phase, the copper contained in these products is considered scrap and may be collected and recycled, thus reentering the cycle together with primary copper. A graphical overview of the model as implemented into a system dynamics software (Vensim from Ventana Systems, Inc.) is given in Figure 1. The structure of the model and the assumptions were cross-checked in a global survey with experts from the copper industry and related organizations.

In contrast to regional models, foreign trade flows are not included in the global model because the system boundaries enclose the entire planet. Historical data on copper mining, production, and use were utilized to estimate current waste and recycling flows and to account for copper stocks in use and in landfills. We used data for the past century (1910–2010) to simulate current waste flows because several copper applications remain in the use phase for several decades and exhibit broad lifetime distributions. As lifetime data and particularly lifetime distributions for different end-use sectors are rare, we used Gaussian distributions for the lifetime model (cf. Supporting Information for more detail). 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 1) and the fabrication of semifinished goods for which both new scrap coming from manufacturing of end-use products and high grade EoL scrap are directly remelted together with copper cathodes. A detailed description of the technical processing of copper from ores over concentration, refining, fabrication of semifinished goods to the technical aspects of copper recycling, and recovery from different scrap types is provided in the Supporting Information.

Generating estimates for collection and recycling rates for each end-use sector or 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 reported production data taking into account the technical aspects of postconsumer scrap treatment (see Supporting Information). In order to enable 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 a simplified example (1 EoL flow which follows 1 path through the technical recycling process, no temporary stocks of scrap or cathodes) of the method to calculate the EoL collection rate as a function of reported production data in order to enable the conservation of mass over time. The IDs for fast identification of the flows in the equations refer to Figure 1.

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 from postconsumer flows for each year is calculated as

$$\begin{aligned}\text{Secondary postconsumer copper } [\mathrm{i}] \\ = \text{Total copper use } [\mathrm{s}] - \text{Primary copper } [\mathrm{a}] \\ - \text{New scrap } [\mathrm{j}]\end{aligned} \tag{1}$$

where the total copper use in a year is set to be equal to the fabrication of semifinished goods. From the waste management perspective, the tonnage of secondary metal from postconsumer flows for each year is calculated as

$$\begin{aligned}\text{Secondary postconsumer copper } [\mathrm{i}] \\ = \text{Total EoL flow } [\mathrm{e}] \cdot \mathrm{CR} \cdot \mathrm{TE}\end{aligned} \tag{2}$$

where CR is the collection rate of postconsumer applications and TE is the technical efficiency of EoL scrap recycling (dismantling, disassembling, smelting, and refining). From these two simple equations the EoL collection rate can be extracted as

$$\begin{aligned}\mathrm{CR} = (\text{Total copper use } [\mathrm{s}] - \text{Primary copper } [\mathrm{a}] \\ - \text{New scrap } [\mathrm{j}])/(\text{Total EoL flow } [\mathrm{e}] \cdot \mathrm{TE})\end{aligned} \tag{3}$$

In the copper flow model we account all EoL flows leaving the end-use sectors to 6 different waste fractions (cf. Figure 1) which are then collected and separated with different efficiencies ending (if not lost) either in the high-grade fraction for direct melt [h] or in the flow for scrap smelting and refining [r]. The higher level of detail in the recycling part of the model results in a higher complexity for the calculation of EoL collection rates and high-grade scrap fractions (cf. Supporting Information, Section

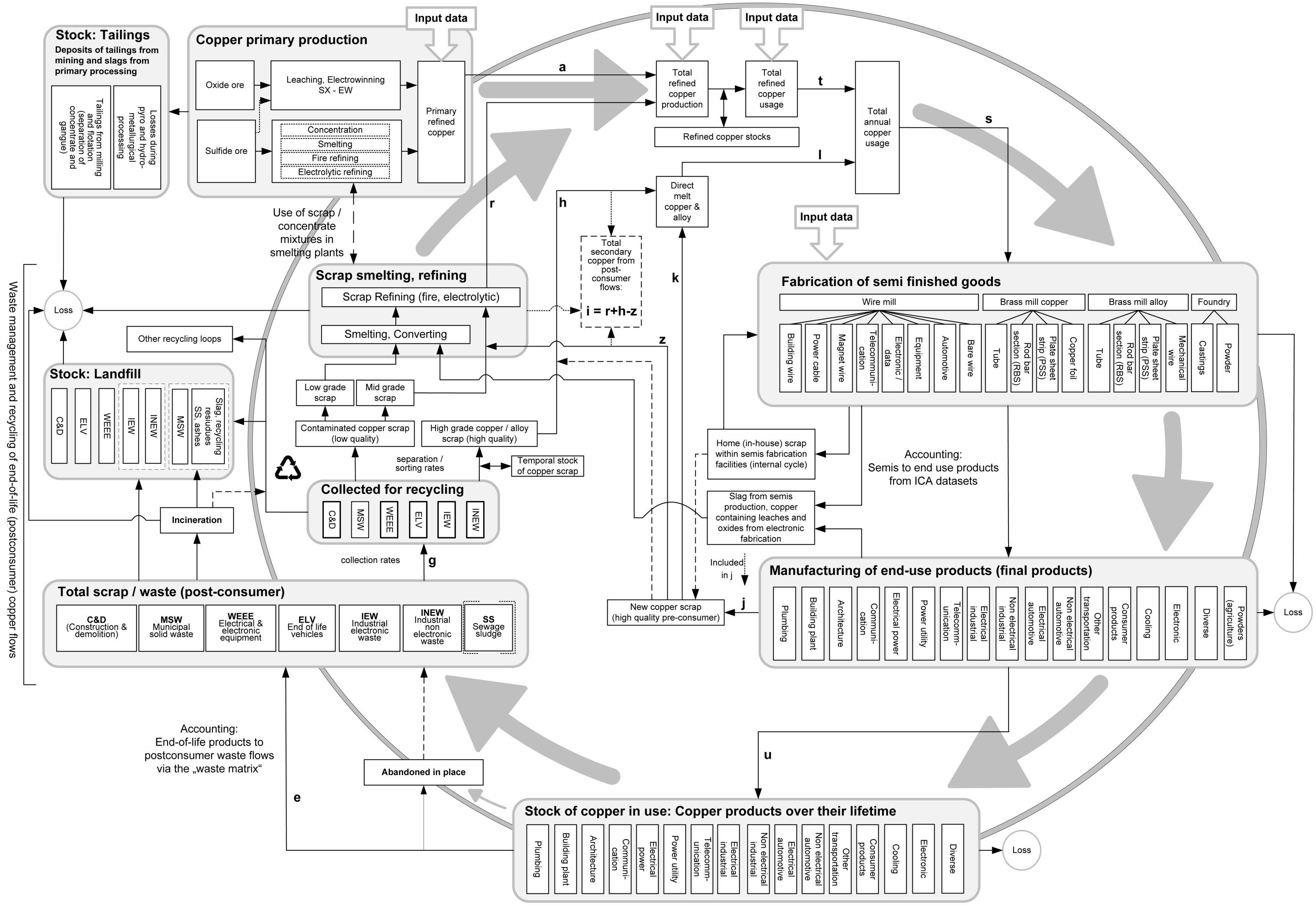


Figure 1. Structure of the global copper flow model. Dashed flows might exist in reality but are not implemented in the model due to the lack of data or due to reasons of simplification.

"Recycling Indicators"). However, the basic methodology remains equal to the system described above.

Uncertainty Evaluation. Different approaches were taken to evaluate the effect that uncertainties in input variables have on the calculated flows and recycling rates:

- Simple range analysis: here, the expected values and standard deviations of the lifetime distributions were varied as a block. That is, first, all expected values of the lifetime distributions were assumed to be a certain percentage above or below the values used in the base simulation. Then the procedure was repeated for the standard deviation.
- The shape of the lifetime distributions was varied.
- Stochastic (Monte Carlo) analysis: for this, ranges were defined for the expected value of the lifetime distributions for each end-use sector and the fabrication efficiency of copper end-use product (also for each end-use sector), and the values used in the simulation were allowed to vary randomly within those ranges. Based on this setup, the model was run iteratively 10^5 times, capturing the calculated recycling indicators for each run and extracting a density function of the results.

RESULTS AND DISCUSSION

Global Stocks in Use and Annual Waste Flows. The global annual primary copper production has increased from 0.85 Tg at the beginning of the 20th century to approximately 16 Tg in 2010. A significant part of the cumulative copper production is still bound in both durable and consumer goods in use today—whether copper entered the technosphere for the first time or it has already been recycled one or more times. The size of this anthropogenic stock and the flows from this stock into the global waste management system are a key element in the estimation of various recycling indicators. Our estimates of these two variables, shown in Figure 2, are based on primary production data since 1910 and assumptions on the distribution of end uses and their lifetime distributions.

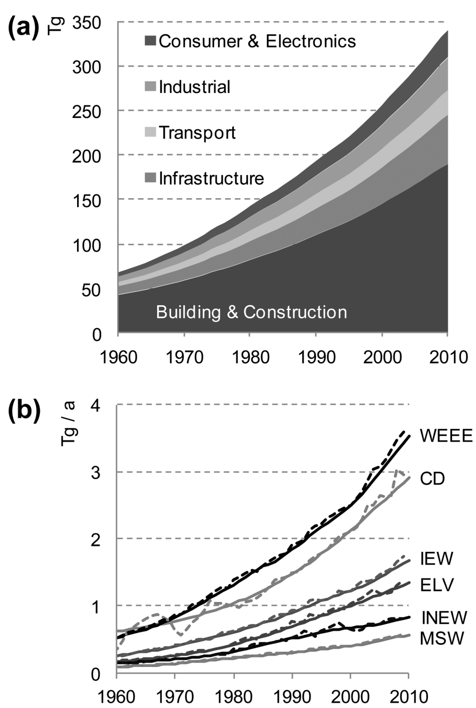


Figure 2. Copper stocks in society and estimated annual waste flows for the period 1960–2010. Tg = million metric tons.

Comparable figures for copper stocks in use have been previously published.[25,26] On the basis of a dynamic stock approach, the global stocks in 2006 were estimated at 330 Tg,[25] which fits very well to the results derived in this study. Also when regarding the global copper stock in use per capita resulting from the model (50 kg/capita when assuming a global population of 7 billion people), the results are in line with previous estimates between 35 and 55 kg/capita.[16,20] However, estimates of copper scrap flows on a global level are rare, not least because of a lack of empirical data. The International Copper Study Group (ICSG) estimated the total amount of copper in global waste streams for the year 2009 at around 12 Tg[27] which is only slightly above the results of this simulation (cf. Figure 2b).

An important observation in Figure 2b is that there is little difference between the estimates obtained by using fixed (average) lifetimes as opposed to lifetime distributions (in this case: Gaussian distributions). When using the former, the year-to-year variability in copper use is directly transferred to the waste flow. In contrast, the use of lifetime distributions has the effect of reducing year-to-year variability in the waste flows by distributing the variability in copper use to several years. However, the difference between the two approaches is generally minimal as long as the average lifetime and the mean of the Gaussian lifetime distribution are the same. Because of the steadily increasing use of copper in the past century, a difference of a few years in the assumed average lifetime or lifetime distribution of products can potentially lead to significant changes in the estimated waste flows. This aspect will be considered in detail below.

By using the dynamic model, it is possible to distinguish between the average lifetime of copper in products and the average age of copper scrap leaving the use phase. The average expected lifetime for copper products in 2010 (weighted by tonnage and based on the lifetime distribution for each product type) was slightly over 25 years, while the average age of waste generated in that same year was slightly over 21 years. Therefore, there is a mismatch between the annual waste (amount and structure) collectable at any given year and the use (amount and structure) one average lifetime prior to that year. This is shown in principle in the Supporting Information and is illustrated in particular for the year 2010 in Figure 3.

The average age of copper in-use stocks can be estimated by calculating the average age for every end-use sector (amount in

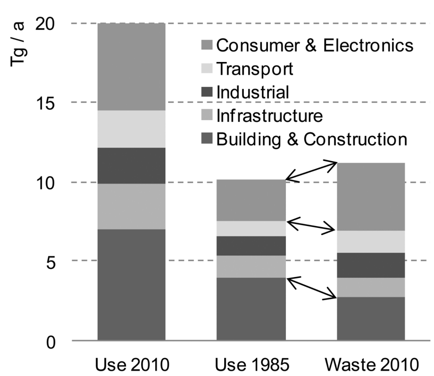


Figure 3. Magnitude and structure of copper scrap flows for 2010 compared to the magnitude and structure of copper use in that same year and in 1985 (one weighted average lifetime prior to 2010). Note that the use in this case refers to the flow entering the use phase [u] (cf. Figure 1).

dx.doi.org/10.1021/es400069b | Environ. Sci. Technol. 2013, 47, 6564–6572

use weighted by its age) which is then weighted according to its share of the total stock and finally summed up. The resulting value for the average age of the current copper stock in use is about 14 years—an at first sight low figure. However, this figure is justified by the continuously increasing global demand, strongly depending on the development of the world economy and particularly forced by the rapid development of infrastructures in emerging countries such as China, India, or Brazil.

Secondary Copper and Stocks of Deposited Material. Sources of secondary copper are old copper scrap (from EoL products) and new scrap (from fabrication residues). The estimated yearly amount of secondary refined copper as well as the amount of directly remelted copper from new and old scrap are shown in Figure 4. In contrast to old scrap, which mainly re-enters the cycle as refined copper, most new scrap is directly remelted. However, there is a fraction of new scrap (approximately 10%) and production residues such as slags and copper containing solvents which are mixed with contaminated low grade old scrap within the scrap smelting and refining process (cf. Supporting Information for more detail). The increase of scrap refinery production in recent years is a result of growing refinery capacities in Asia, particularly in China.[3,28]

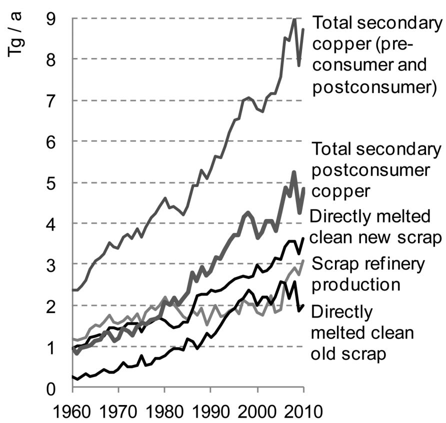


Figure 4. Total secondary copper (direct melt [l] + secondary refinery production [r]) and the contributions to this by direct melt from old [h] and new scrap [k], and by secondary refined copper [r] (mostly from old scrap but also including around 10% of annual scrap and residues from fabrication). The Flow IDs refer to Figure 1.

In the model, most of the copper in end-of-life applications which is not collected for recycling ends up in the stock of landfill. During the useful lifetime of products, smaller amounts of copper are dissipatively lost, e.g., due to corrosion and abrasion. Furthermore, during scrap separation and disassembling, a non-negligible amount of copper is lost to other metal recycling loops[6,9] where copper ends up in slags or remains in the recycled metal in the form of impurities. A further sink is copper that remains in place after its useful lifetime and that is not available for collection ("abandoned in place"). The accumulated copper stock in landfills and the aggregated total loss of copper to the sinks described above are shown in Figure 5. Regarding our estimates of deposited copper, it has to be considered that landfilled copper as described above and shown in Figure 5 only refers to deposits of anthropogenic copper from EoL waste flows (postconsumer scrap) and fabrication residues. Tailings from mining and production (particularly losses during milling (copper minerals remaining in gangue), flotation, and leaching of ores but also residues from smelting of concentrates and solvent extraction) are not included in the stock of copper on landfills. Applying the efficiencies of ore and concentrate processing described in the Supporting Information, the accumulated tailings from mining (over the past century) are estimated to be around 100 Tg. However, we emphasize that material losses to tailings during mining, milling, and flotation occur before the copper enters the human technosphere as metal. Note that the estimates of global metal stocks (≈350 Tg in use and ≈200 Tg in landfills/dissipated/abandoned in place) can be verified (to a first approximation) by comparing them to the accumulated mine production over time (≈550 Tg between 1910 and 2010).

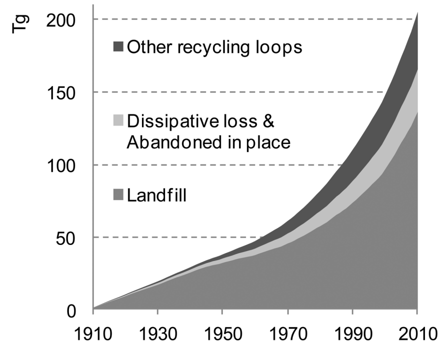


Figure 5. Accumulation of copper on landfills and further copper losses within the anthropogenic copper cycle over the past 100 years. Note that losses during mining and primary metal production are not included in this depiction.

The global waste flows resulting from the model simulation, together with diagrams of all aggregated flows, are provided in the Supporting Information. Of the estimated 10.85 Tg copper leaving the use-phase in 2010 (postconsumer), the effectively recycled copper from EoL flows is estimated at 4.8 Tg. Note that the waste basis for the calculation of recycling indicators does not include the dissipative losses.

The main target of this work was to provide a comprehensive overview on the current status of copper recycling at a global level. To this end, eight recycling indicators were calculated on the basis of flows extracted from the model (flow IDs refer to Figure 1):

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

These indicators are to a greater or lesser extent used in the recycling literature[9,23,29,30] and their definitions are widely accepted.[31,32] More detail on the indicators (definitions and flows in the model) is provided in the Supporting Information.

Due to the year-to-year variations in global copper flows, the calculated recycling rates vary over time as displayed graphically for the period 2000−2010 in Figure 6 (see the Supporting Information for tabulated values). Inspection of Figure 6 reveals the strong correlation between several indicators due to the similarities in their definition.

The recycling indicators shown in Figure 6 are average global values over all scrap types. However, the model provides deeper

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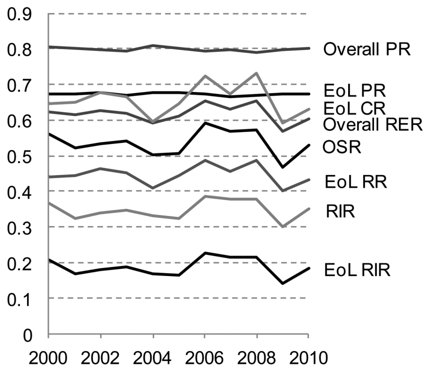

Figure 6. Development of recycling indicators for the period 2000–2010. Acronyms: PR, Processing Rate; CR, Collection Rate; RER, Recycling Efficiency Rate; OSR, Old Scrap Ratio; RR, Recycling Rate; RIR, Recycling Input Rate.

insight into the recycling efficiency of different waste fractions. This was made possible by accounting the discarded products to different waste types and by defining separation, disassembling, and recovery efficiencies for these waste fractions—see the Supporting Information for more details on the assignment of EoL scrap to scrap types. Estimated average recycling efficiencies for the years 2000–2010 and the standard deviations for each waste type are listed in Table 1. These scrap type based estimates on recycling efficiencies are essential in specifying material losses during the recovery process. In this context, it is important to keep in mind that the model is based on a closed mass balance for every year and will always match reported historical production data. This means that if the recycling rates in Table 1 are increased for one scrap type they will automatically be decreased in a compensatory amount for the other scrap types.

Beyond the estimates at the level of scrap type, it is theoretically possible to calculate selected recycling indicators at the level of individual end-use sectors. In practice, however, this attempt is of limited value because of data issues: while estimates were prepared for the technical recovery efficiencies of copper from individual scrap types (cf. Supporting Information), these estimates are not available at the level of individual copper containing EoL products. What this means is that, in order to distribute the scrap-type-based estimates to the different end-use products in the model (by backward calculation), the assumption needs to be made that all product types (end-use sectors) going into one scrap type are recycled with the same average efficiency assumed for this specific scrap type (for example electronics, parts of electrical industrial waste and parts of EoL cooling systems are all accounted to WEEE). Therefore, while a listing of estimates is provided for the different product types in the Supporting Information, the numbers are not as robust as the assumed average scrap type based efficiencies (cf. Table 1).

Evaluation of Uncertainties and Sensitivity Analysis. Because the total amount of copper within total annual end-of-life flows is the basis for several key recycling indicators which measure the efficiency of waste management and raw material recovery (EoL CR, EoL RR, overall RER), this variable has a strong effect on the resulting estimates. Therefore, an analysis of the sensitivity of recycling indicators on changes in copper scrap tonnage is in order. Within the model, the yearly amount of copper waste is calculated by the lifetime approach as described above and in more detail in the Supporting Information. That is, the estimates of annual end-of-life flows are based on the historical end-use structure of copper and assumptions of the average lifetimes and lifetime distributions of these end uses (before they become waste and available for recycling). As historical copper production and use data are comparatively well reported (cf. Supporting Information), the assumption of an average lifetime for copper in each end-use appears to be the least robust estimation in the model. Therefore, to investigate the effect of changes in lifetimes and lifetime distributions, an initial sensitivity analysis was carried out. In a first step, we assumed that all average lifetimes (in the form of expected values of Gaussian distributions) are off in the same way (either all shorter or all longer) and in the same proportion. In the case of a ±15% error in the average lifetime estimates, the error transmitted to the recycling indicators is ≈5% (absolute value) for the case of overall RER and EoL RR. The direction of change is as follows: the longer the lifetime, the higher the recycling rate. This is a result of the increasing use of copper: longer lifetimes mean the amount of available copper containing scrap is lower because less was used in earlier years (historical copper use continuously increased in the past), thus making the denominator smaller. The same is true for the EoL collection rate, but the impact here is larger (≈7%). The RIR, the EoL RIR, the OSR, and the PRs (EoL and overall) are essentially not affected by changes in lifetime assumptions (≈1% change).

In a second step, we varied the value of the standard deviation of the normally distributed lifetime functions revealing that the effect of variations of the breadth of lifetime distributions is negligible compared to the effect of changes of expected values (see Supporting Information for detailed figures). Next, we explored the effect of variations in the shape of the lifetime distributions. Normally distributed functions are symmetrical around their mean, which is at the same time their median and their mode. Because there is little empirical information on lifetime distributions of different copper applications to be found in the literature, especially at the global level, the analysis presented above is based on the assumption of Gaussian (normal) distributions. However, typical lifetime distributions

Table 1. Estimated Recycling Rates at the Level of Waste Type[a]

Waste type	EOL Collection Rate	Deviation over time	EOL Recycling Rate	Deviation over time	EOL Recycling Processing Rate	Deviation over time
C&D	0.72	0.06	0.65	0.06	0.90	0.0
MSW	0.05	0.02	0.01	0.00	0.20	0.0
WEEE	0.63	0.06	0.34	0.03	0.54	0.0
ELV	0.91	0.04	0.49	0.02	0.54	0.0
IEW	0.66	0.06	0.46	0.04	0.69	0.0
INEW	0.68	0.06	0.50	0.05	0.74	0.0

[a]Note that the mean and standard deviation relate to the time period 2000-2010. Scrap types are as follows: Construction and Demolition Waste (C&D), Municipal Solid Waste (MSW), Electrical and Electronic Equipment Waste (WEEE), End of Life Vehicles (ELV), Industrial Electrical Equipment Waste (IEW), and Industrial non Electrical Equipment Waste (INEW).

from quality, safety, and environmental engineering are skewed (cf. Supporting Information). Thus, we compared Gaussian distributions to log-normal, χ^2, and Weibull distributions, and obtained similar results to the analysis based on varying the standard deviation of the Gaussian distributions: The effect of changing the shape (functional form) of the lifetime distributions is small compared to the effect of changes in average lifetimes. Hence, further analyses should focus on the mean values of lifetime distributions.

In addition to uncertainties in the average lifetimes, there is considerable uncertainty concerning the percentage of new scrap within the total waste fraction. The amount of new scrap depends on assumptions regarding the fabrication efficiencies of different end-use products. Despite a comprehensive literature review and a survey among experts from the copper industry and related research institutes (see Supporting Information), the fabrication efficiencies used for the simulations still contain a degree of uncertainty.

Assuming the historical mining and production data to be reliable, an approach had to be found for dealing with the above-mentioned uncertainties. In principle, each of the assumptions for each end-use sector may vary independently from the others. Thus, a possible approach would be to simulate all possible combinations for different degrees of variability. This can be approximated through stochastic (Monte Carlo) methods. The advantage of this approach compared to simple minimum and maximum scenarios—in which all uncertain variables at the same time are set to their minimum or maximum value—is that the density of possible results can be extracted from the simulation data. For the evaluation of the model, we let the uncertain variables randomly change their values within a defined spread: mean values of lifetime distributions for different end-use sectors were allowed to vary by ±15% (relative) while fabrication efficiencies were allowed to randomly vary by ±5% (absolute) in each simulation run. The model was then run 10^5 times, extracting the calculated recycling indicators for each run. The result is a distribution of the density of different results over time. Similar methodologies to analyze uncertainties have been presented by Pruyt et al.[33,34] The basic consideration of this approach is that for one single uncertain variable we do not know if we hit the right average value, but the likelihood that all values were chosen too low or too high is comparatively low. This thought is reflected by the density distribution of the results based on the stochastic simulation.

The results of the Monte Carlo simulation allow two additional views of the calculated recycling rates: the first view is similar to Figure 6 but adds the variations caused by uncertainties in the assumptions for the useful lifetime and fabrication efficiency of copper-containing products. This is shown for all indicators in the form of a boxplot and for the example of the CR as a distribution over time in the Supporting Information (cf. depiction in the abstract). Because the global flow model used here cannot completely reflect the real complexity of the copper market (e.g., time effects related to changing copper prices such as stockpiling of semifinished products and copper-containing scrap), a cumulative view of the recycling indicators over time offers a more robust estimation of the efficiency of the copper recycling system. This aggregation over a period of time (2000–2010) was performed for all eight recycling indicators considered here and is shown in Figure 7. The EoL CR is affected most strongly because both variations in average lifetimes (through the total amount of annual copper waste) and variations of fabrication efficiencies (secondary copper which is not available from new scrap is attributed to recycling of EoL scrap) have a direct impact on this indicator. The EoL RR as a product of EoL PR and EoL CR is affected due to the same reasons. The same applies to the Overall RER. The Old Scrap Ratio (OSR) is directly affected by both the EoL CR and by variations of the fabrication efficiency which mediates the annual amount of new scrap and residues from fabrication. The other indicators only show little variation (Figure 7, bottom row). It is therefore possible to provide estimates of the recycling rates considering both the variation over time and that introduced through uncertainties in the underlying

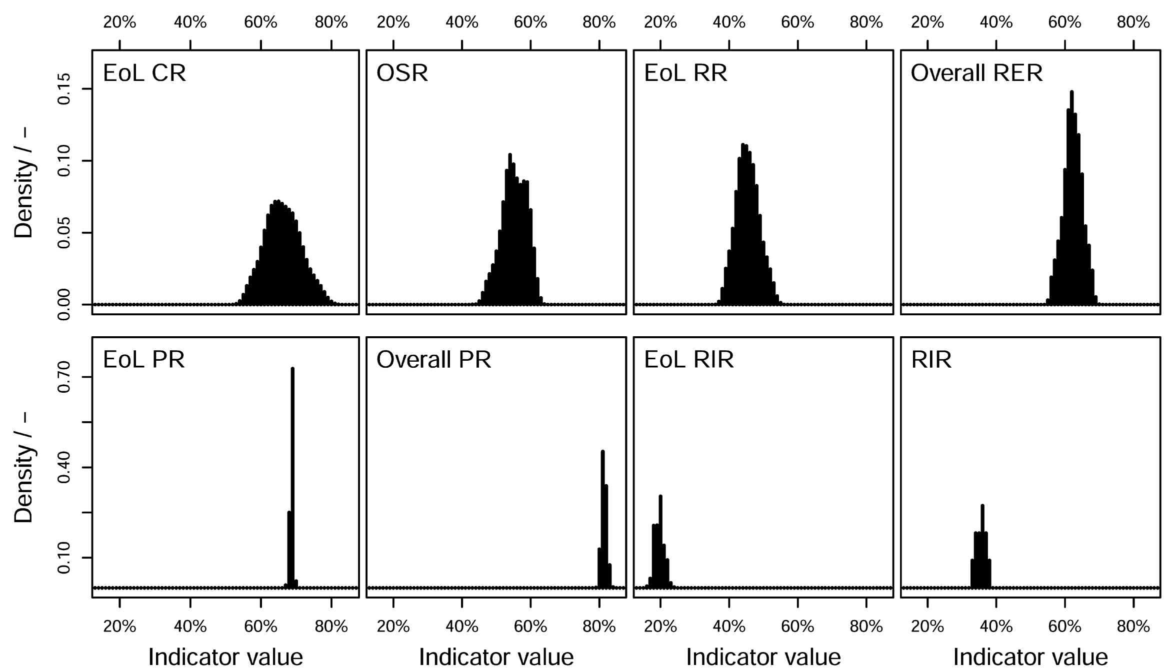

Figure 7. Average density functions (2000–2010) of all recycling indicators considered. Particularly, the EoL CR is affected by uncertainties concerning the average lifetimes of products. In addition, the OSR is strongly affected by variations of the fabrication efficiency which regulates the amount of new scrap coming from fabrication of end-use products.

dx.doi.org/10.1021/es400069b | Environ. Sci. Technol. 2013, 47, 6564–6572

assumptions of the model on the basis of Figure 7. These estimates are tabulated in the Supporting Information.

A uniform estimation of all indicators shown in Figure 7 at a global level is not yet available in the literature. However, several estimates for the EoL RR of copper, which is the most important indicator when analyzing the efficiency of EoL scrap treatment, have been performed in previous studies on the basis of expert interviews and estimates of global scrap availability.[23,28,32] In these studies the EoL RR of copper was estimated to be slightly above 50% but the average value derived from the distribution shown in Figure 7 taking into account both variations over time and variations due to uncertainty is around 45%. The RIR is the most frequently published recycling indicator with the least variation among different literature sources and is estimated at around 35% on a global level.[3,32] This is because there is no need for information on scrap availability and scrap composition in order to calculate this indicator as it directly results from the difference between total production and mining data.

The uncertainties described above also have an impact on the estimates for copper stocks in use and in landfills and for the total annual copper end-of-life flow. These are displayed in Figure 8.

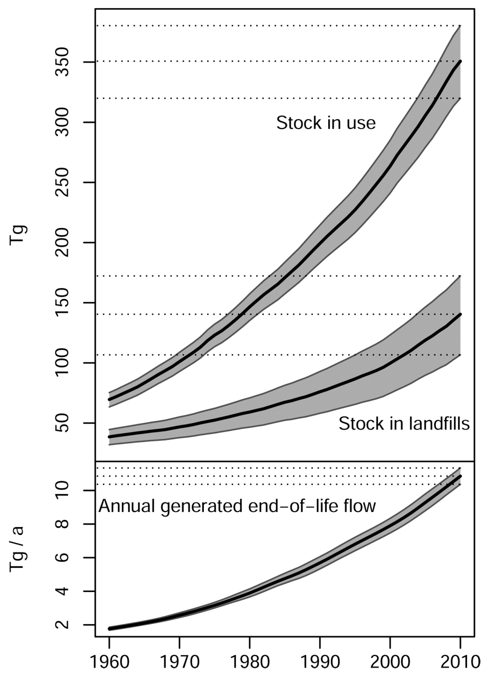

Figure 8. Effect of uncertainties on the calculation of stocks in use and in landfills and on the annual end-of-life flows.

Particularly, the spread of stocks in landfills shows the largest variability. This is a direct result of variations of the EoL CR (uncertainty in the magnitude of copper scrap collected for recycling, the remaining copper scrap is mostly accounted to the stock in landfills).

The results from the model simulation and the uncertainty evaluation underline the complexity of determining metal cycles and defining recycling indicators with one single figure, as both temporal variations and uncertainties have to be taken into account. Dynamic life cycle models as presented in this work are the basis for gaining a better understanding of the material system as a whole. However, to ensure that the material flows derived from the model are realistic, the simulated flows have to be in line with data from available empirical statistics. In the case of copper, global production data for mining (primary production), refinery output, and semifinished goods fabrication are well reported. The uncertainties are mainly restricted to waste flows which are generally not well reported, especially when regarding specific material flows. As most empirical data are usually collected on a regional basis, future work on the copper model will focus on breaking down the global model into different regions which are linked through foreign trade flows in each step of the value chain.

Moreover, the methodology developed for the material life cycle of copper is applicable to further industrial metals which are, analogous to copper, currently recycled in large amounts such as steel, aluminum, nickel, lead, or zinc. Current raw material markets show rapid changes both on the supply (primary and secondary) and the demand side, but static metal cycles are not capable of reflecting this. Therefore, further dynamic approaches are needed because understanding the historical development of primary and secondary metal production is the basis for projecting future developments, for the early identification of possible bottlenecks and for analyzing the potential of higher efficiencies of metal recycling. In this context, we intended to give a detailed view of the life cycle of copper and to introduce a basic methodology of balancing yearly postconsumer flows which might contribute to future studies in the field of industrial ecology.

■ ASSOCIATED CONTENT

Supporting Information

Detailed overview of the model, input data and the method of calculating stocks and flows, details on the survey, definition of recycling indicators, and additional results. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The work leading to this publication was funded by the International Copper Association (ICA). In particular, the authors would like to thank Colin Bennett and Géraud Servin from ICA for their support in securing both relevant data and industry contacts. Input from the International Copper Study Group (ICSG), the International Wrought Copper Council (IWCC), the Institute of Scrap Recycling Industries, the U.S. Geological Survey, the European Copper Institute, the Copper Development Association, Deutsches Kupferinstitut, and several companies in the copper industry is gratefully acknowledged. However, statements presented here are not the official opinion/position of these organizations/companies. The responsibility for the content of this paper remains with the authors.

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