

# Flow and Fates of Discarded Copper in Sofia, Bulgaria, and New Haven CT, USA

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# Flows and Fates of Discarded Copper in Sofia, Bulgaria, and New Haven, CT, USA

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## ABSTRACT

In order to better understand the fate of copper following its use, the discard flows of copper were analyzed in Sofia, Bulgaria, and New Haven, CT, USA. These cities were chosen to compare discard copper generation and recovery between a city in a developed country and a city in a developing country. The comparison between these two cities can be problematic due to their different relative sizes, and generalizing the results to other cities cannot be done without some error. However, as the first study of its kind, this study provides insights into the relative copper recovery rates in different socioeconomic contexts. The total yearly per capita copper discards from in-use stocks in Sofia were found to be about 1.9 kg/person (for year 2003), while New Haven has total yearly per capita copper discards from in-use stocks of about 4.7 kg/person (for year 2000). The associated recovery rates for copper in both cities are quite high, at about 87% in New Haven, and 97% in Sofia. The higher per capita copper discards and the lower recovery rate in New Haven is thought to be attributable to the higher average income level relative to Sofia.



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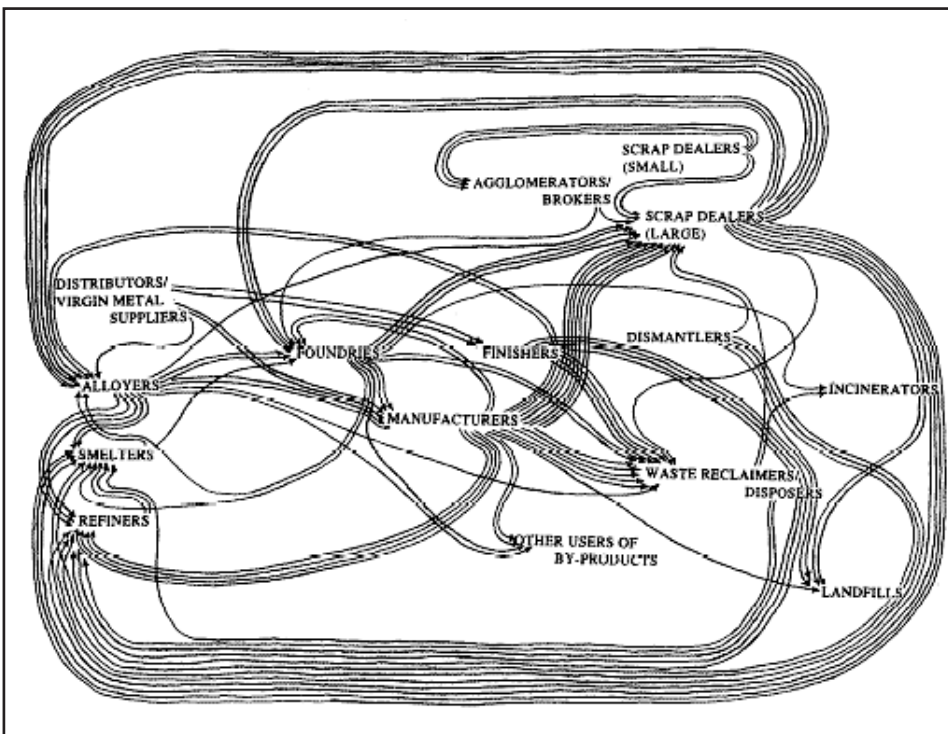


## INTRODUCTION

Discard flows are quite difficult to quantify with any precision. Other constituents of materials cycles – extraction of virgin ore, new scrap entering processing, exports of products, etc. – are often relatively well-characterized. In contrast, there are few mechanisms for capturing data related to industrial waste, the abandonment of unserviceable automobiles, the disposal of construction debris, and the like (e.g., Spatari *et al.* 2002).

There are three additional aspects of discards that render the topic challenging. One is the frequent reuse of discarded products of various kinds, especially in developing countries (e.g., Maldonado and Sethuraman 1992; Li 2002; Ketlogetswe and Mothudi 2005). By their very nature, no records are kept of these transactions. The second aspect is the large number and great diversity of participants in the formal scrap industry, a situation illustrated by Sagar and Frosch (1997) in their classic “spaghetti diagram,” reproduced in Figure 1. Most of the transactions among these participants are private, and few reporting requirements exist. Finally, materials discarded into municipal and industrial waste streams of various kinds are often captured and sold back into use by disadvantaged scavengers (e.g., Medina 1997, 2000; Agunwamba 2003), again with no accompanying data records.

**Figure 1** Copper Scrap Industry Interactions in New England. Each line represents one set of transactions between categories of interviewed firms. (Reproduced from Sagar and Frosch, 1997 by permission of Elsevier Science, Ltd.)



From this perspective on discards, and from the realization that better information is needed on the discard portion of metal cycles, the present paper addresses the discards of copper. Other studies have been carried out to analyze city-scale copper *in-use stocks* (van Beers and Graedel 2003; Sörme *et al.* 2001), but the present work is the first to our knowledge to address copper discard flows in a quantitative fashion at the city scale. The demand for copper is relatively high vis-à-vis its natural available reserves (Kesler 1994). Understanding discard rates and the efficiency with which copper is recovered or sees secondary uses is therefore important.

This study attempts to assess the present state of copper *discard flows* in the cities of Sofia, Bulgaria and New Haven, CT, USA, the former a large city undergoing economic development, the latter a medium-sized city with modest industry and in which Yale University is the largest employer. The mass of copper discards is quantified for different waste streams, and the copper recovery rates are estimated for each of these streams.

The paper focuses primarily on the copper discard flows leaving *in-use stock*. These flows are resolved into the following waste streams:

- municipal solid waste (MSW);
- waste from electrical and electronic equipment (WEEE);
- infrastructural waste (mainly cables for electrical distribution and telecommunications);
- construction and demolition debris (C&D);
- waste from end-of-life vehicles (ELV);
- hazardous waste (HW);
- industrial waste (IW).

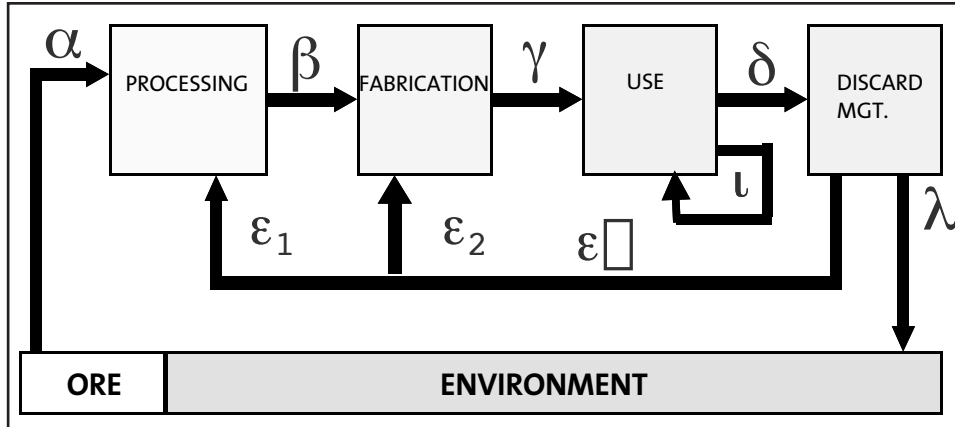
We also discuss new scrap, which comes from the manufacturing stage of copper's lifecycle and not from in-use stocks. Sewage sludge is not addressed in this paper.

A simplified picture of the anthropogenic copper life cycle is shown in Figure 2. The flows are as follows:

- $\alpha$  rate of extraction of copper-bearing ore
- $\beta$  rate of flow of refined copper
- $\gamma$  rate of flow of copper in products entering use
- $\delta$  rate of flow of copper in discarded products
- $\epsilon$  rate of flow of recycled copper ( $\_1$  for reprocessing,  $\_2$  for direct reuse in products)
- $\iota$  rate of flow of copper in reused products
- $\lambda$  rate of flow of copper to landfills

The present work attempts to characterize and quantify flows  $\delta$ ,  $\epsilon$ ,  $\iota$ , and  $\lambda$ .

Figure 2 The Simplified Copper Cycle. The Greek letter flows are discussed in the text.



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## METHODOLOGY

The two cities in which this study was conducted are considerably different in size and population. New Haven's population is 123,626 (year 2000) in an area of 49 km<sup>2</sup>, while Sofia has 1,221,157 people (year 2004) in an area of 245 km<sup>2</sup>. In both New Haven and Sofia, information was gathered through governmental and company published data, and through personal interviews with sector experts (e.g., copper scrap dealers).

However, the emphasis of approaches used in the two cities varied due to differences in data availability. In New Haven, data were more readily available through online sources and upon request. The New Haven discard study (but not the Sofia study) was preceded by research that estimated the copper stock residing in the city (Drakonakis *et al.* 2007). This approach allowed the copper discard generation estimates to rely heavily upon the lifetimes of different in-use stock categories. For instance, the total mass of copper in refrigerators entering the discard stream can be estimated by dividing a lifetime estimate (19 years for refrigerators) into the total in-use stock of copper in refrigerators.

Pertinent data in Sofia were not as readily available, even after extensive requests to potential data sources. The copper generation rates were instead derived from the estimate of the total copper collected for recycling in the city, estimates of the percent contribution of each discard stream to that total amount, and estimates of the copper recovery rates for each of the discard streams. Where possible, the copper generation rates for the sub-streams within the main waste streams were determined directly through interviews with relevant businesses.

Trans-city boundary transfers of copper scrap were an issue addressed in some detail. Both studies faced the challenge of precisely identifying the spatial origin of the copper collected for recycling within the city boundaries. No official city-level data collection on this topic exists, nor is it collected informally by individual scrap dealers. In New Haven, this obstacle was overcome by relying heavily on product

lifetimes of in-use stocks, whereas in many cases in Sofia the total amount of copper collected for recycling in the whole country was the only information available, requiring scaling down to the city level based upon population.

In New Haven, all the available data between 1996 and 2005 were averaged in order to minimize the distorting effects of incidental events and to get a good estimate for the year 2000. In Sofia, much of the relevant data were generated only in recent years. Even when data were available for longer periods, changes in environmental policies, data collection practices, and data consistency did not allow the use of older data. As a result, data were used primarily from the most recent years – 2003 and 2004.

The recovery rate quantified is adapted from the convention of Quinkertz *et al.* (2001) and Norgate (2004) and distinguished from the overall recycling rate. The first stage in recycling is the actual recovery of the material. This recovery rate represents the social aspect of the discard management system. The second stage in recycling is the recycling efficiency, or the technological ability to extract copper from a specified object (e.g., a car). The overall recycling rate is the multiple of the recovery rate and recycling efficiency. Utilizing the symbols defined in Figure 2:

$$\begin{aligned} \text{Recovery Rate} &= R_s / \delta \\ \text{Recycling Efficiency} &= \varepsilon / R_s \\ \text{Recycling Rate} &= \varepsilon / \delta \\ &= \text{Recovery Rate} * \text{Recycling Efficiency} \end{aligned}$$

where  $R_s$  is the amount of copper recovered in the first stage of discard management. As the technological extraction of copper (recycling efficiency) occurs almost entirely out of the cities' boundaries, this value was not quantified. This study only quantifies the recovery rate of copper in New Haven and Sofia.

## RESULTS AND DISCUSSION

The level of detail of the results presented in this paper reflects the different methodologies used in Sofia and New Haven. The New Haven study was coupled with a copper in-use stocks study, which allowed greater resolution of the copper generation rates than Sofia. The Sofia study focused more on defining the reuse and recovery rates within sub-streams of the main waste streams.

### Copper End-of-Life Discard Rates

All the municipal solid waste (MSW) of New Haven is transferred for incineration to facilities elsewhere in Connecticut. Therefore, the 7 Mg Cu/yr (0.1 kg Cu/(capita·yr)) generated in this discard stream leave the city and are not recovered. This amount is based on the estimate that 40% of the non-ferrous metal waste stream, which, according to the local discard management firm amounts to 0.05% of the total discard flow, is comprised of copper. As such, New Haven's municipal solid waste has a percent copper content of 0.02%.

In New Haven, the copper discard rate for household and commercial electrical and electronic equipment (WEEE) is 98 Mg Cu/yr (0.8 kg Cu/(capita·yr)). As Table 1 indicates, the largest category of copper discard for domestic WEEE is portable air conditioners, while computers are the largest source of copper in commercial WEEE.

**Table 1 Copper Discard Rates for the WEEE Stream in New Haven**

| Sub-streams                               | Mg Cu/yr    | kg Cu/(capita·yr) * |
|---|-------------|---------------------|
| <b>Household Electrics</b>                | <b>89.7</b> | <b>0.7</b>          |
| refrigerators/freezers                    | 5.2         | 0.0                 |
| washing machines                          | 4.9         | 0.0                 |
| dryers                                    | 2.5         | 0.0                 |
| dishwasher                                | 4.4         | 0.0                 |
| stoves/domestic cooking                   | 7.8         | 0.1                 |
| microwave oven                            | 1.5         | 0.0                 |
| portable air conditioners                 | 50.0        | 0.4                 |
| garbage disposals                         | 2.2         | 0.0                 |
| vacuum cleaners                           | 10.2        | 0.1                 |
| hair dryers                               | 1.0         | 0.0                 |
| <b>Household Electronics</b>              | <b>0.3</b>  | <b>0.0</b>          |
| <b>Commercial “White Goods” Electrics</b> | <b>2.5</b>  | <b>0.0</b>          |
| refrigerators/freezers                    | 0.6         | 0.0                 |
| washing machines                          | 0.1         | 0.0                 |
| dryers                                    | 0.0         | 0.0                 |
| microwave oven                            | 0.1         | 0.0                 |
| portable air conditioners                 | 1.7         | 0.0                 |
| <b>Commercial Electronics</b>             | <b>5.2</b>  | <b>0.0</b>          |
| computers                                 | 4.5         | 0.0                 |
| televisions                               | 0.3         | 0.0                 |
| telephones                                | 0.3         | 0.0                 |
| stereos/radios                            | 0.1         | 0.0                 |
| <b>Total Cu</b>                           | <b>97.7</b> | <b>0.8</b>          |

The MSW and WEEE streams in Sofia are mixed at the point of generation and cannot be disaggregated. This combined waste stream comprises 291 Mg Cu/yr (0.2 kg Cu/(capita·yr)). The generation rate is calculated based on the following estimates: 2,880 Mg Cu/yr for all copper scrap collected for recycling in Sofia (including new scrap), 10% contribution of the mixed MSW and WEEE streams to that total amount (or 288 Mg Cu/yr), and 99% recovery rate for the copper in that stream. With MSW generation rate of 365,600 Mg/yr (2003), it can be inferred that the copper content of the combined MSW/WEEE stream is about 0.08%.

The infrastructural discards for the two cities are reported in Table 2 for New Haven and Table 3 for Sofia. In New Haven, the copper discard generation rate for the infrastructural waste stream is 68 Mg Cu/yr (0.5 kg Cu/(capita·yr)). The Yale

University infrastructural wastes are either electrical cables or transformers, and the estimations for the telephone system are based upon a lifetime estimate of 45 years. The copper discard generation rate in Sofia is 658 Mg Cu/yr (0.5 kg Cu/(capita·yr)). Most of this copper scrap comes from the maintenance of the electrical distribution system.

**Table 2 Rates for Infrastructural Copper Discards in New Haven**

| Sub-stream                     | Mg Cu/yr    | kg Cu/(capita·yr) |
|--------------------------------|-------------|-------------------|
| UI Electric Cable Distribution | 14.6        | 0.1               |
| Transformers                   | 5.0         | 0.0               |
| Yale University Electrical     | 22.7        | 0.2               |
| Power Plants                   | 10.9        | 0.1               |
| Telephone System               | 14.5        | 0.1               |
| <b>Total Cu</b>                | <b>67.7</b> | <b>0.5</b>        |

**Table 3 Rates for Infrastructural Copper Discards in Sofia**

| Sub-stream                             | Mg Cu/yr   | kg Cu/(capita·yr) |
|--|------------|-------------------|
| Electrical distribution infrastructure | 368        | 0.3               |
| Telecommunication infrastructure       | 261        | 0.2               |
| Electrical transport infrastructure    | 28         | 0.0               |
| <b>Total Cu</b>                        | <b>658</b> | <b>0.5</b>        |

The derived copper discard generation rate for construction and demolition debris (C&D) in New Haven is 309 Mg Cu/yr (1.5 kg Cu/(capita·yr)). Table 4 summarizes the breakdown into the different construction and demolition waste categories. Wire and plumbing is broken into two groups each; one group presents the amount of copper leaving in-use stocks, while the other group presents new cuttings (a.k.a. “prompt scrap”). New cuttings represent copper scrap that is generated during initial construction and installation.

The amount of copper generated in the C&D stream in Sofia is estimated to be 229 Mg Cu/yr (0.2 kg Cu/(capita·yr)). This number is based on expert estimation that 7% of the copper generated in the C&D stream is not recovered and on estimation (inferred by conversations with scavengers at the C&D landfill) that each year about 16 Mg Cu is buried in the landfill. Electrical wires are the main source of copper in the C&D stream in Sofia, as the use of copper pipes for water distribution and heating has historically been very limited.

**Table 4 Copper Discard Rates for the C&D Stream in New Haven**

| Sub-stream                              | Mg Cu/yr     | kg Cu/(capita·yr) |
|---|--------------|-------------------|
| Wiring                                  | 80.1         | 0.6               |
| Plumbing                                | 75.1         | 0.6               |
| Other Hardware                          | 5.6          | 0.0               |
| Central Air Conditioning                | 2.8          | 0.0               |
| Elevators, Escalators, Dumbwaiters      | 5.3          | 0.0               |
| Architectural (roofing, gutters, etc)   | 1.2          | 0.0               |
| Other Built-in appliances               | 17.5         | 0.1               |
| Wiring (new clippings – never in-use)   | 120.1        | 1.0               |
| Plumbing (new clippings – never in-use) | 1.5          | 0.0               |
| <b>Total Cu</b>                         | <b>309.2</b> | <b>2.5</b>        |

Tables 5 and 6 report the breakdown of the end-of-life vehicle (ELV) copper discard flow in New Haven and in Sofia. The discard generation rate for the ELV stream is 85 Mg Cu/yr (0.7 kg Cu/(capita·yr)) for New Haven and 318 Mg Cu/yr (0.3 kg Cu/(capita·yr)) for Sofia.

In New Haven, vehicles that travel through, but do not permanently reside and are not registered in the city (non-resident vehicles), are not considered in the ELV calculation. This effectively excludes marine vessels, railcars, and large aircraft. In Sofia, accurate estimates for the discard generation rates for buses, trolleybuses, and trams were obtained. However, the estimate for passenger vehicles in Sofia is very rough; most likely the “other vehicles” category contains primarily passenger vehicles.

**Table 5 Copper Discard Rates for the ELV Stream in New Haven**

| Sub-streams     | Mg Cu/yr    | kg Cu/(capita·yr) |
|-----------------|-------------|-------------------|
| Automobiles     | 82.7        | 0.7               |
| Air             | 0.2         | 0.0               |
| Marine          | 2.1         | 0.0               |
| Rail            | 0.0         | 0.0               |
| <b>Total Cu</b> | <b>85.0</b> | <b>0.7</b>        |

**Table 6 Copper Discard Rates for the ELV Stream in Sofia**

| Sub-streams     | Mg Cu/yr   | kg Cu/(capita·yr) |
|-----------------|------------|-------------------|
| Passenger cars  | 35         | 0.03              |
| Buses           | 5          | 0.00              |
| Trolleybuses    | 6          | 0.00              |
| Trams           | 13         | 0.01              |
| Others          | 259        | 0.3               |
| <b>Total Cu</b> | <b>318</b> | <b>0.3</b>        |

In both Sofia and New Haven, the hazardous waste (HW) stream is not a source of recoverable copper leaving use. In both cities, industrial generators of small amounts of copper-containing hazardous waste were identified, but because this copper comes from the manufacturing stage of the copper life cycle, it was not further pursued in this work.

The generation rate of obsolete industrial machinery for New Haven is only 17 Mg Cu/yr (0.1 kg Cu/(capita·yr)). In contrast, obsolete industrial machinery is a major source of discard copper in Sofia, amounting to about 870 Mg Cu/yr (0.7 kg Cu/(capita·yr)).

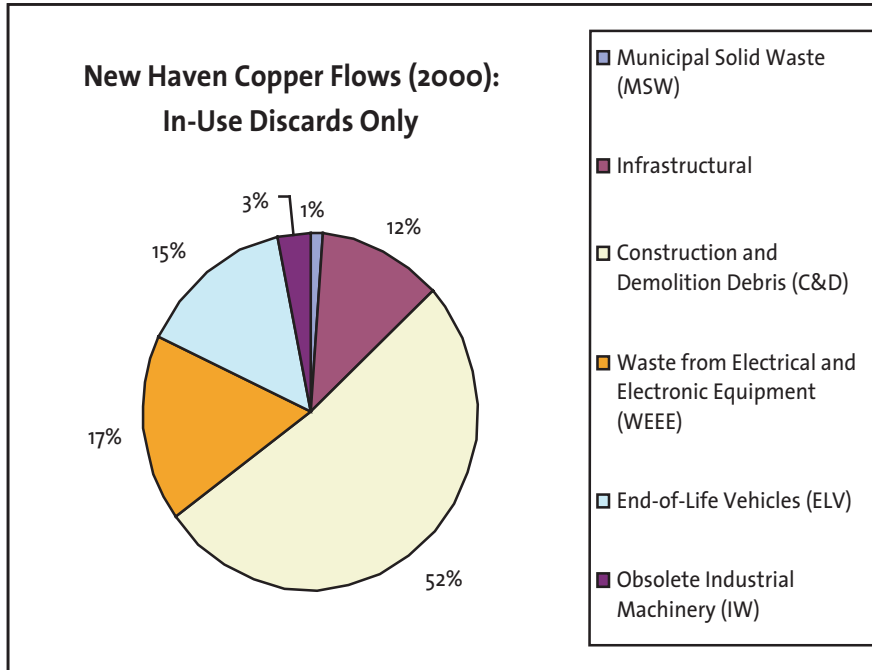
Table 7 summarizes the end of life copper discard rates in Sofia and New Haven, separated by waste stream and given in both total and per capita flows. The total annual generation rates are about 2,400 Mg Cu/yr or 1.9 kg Cu/(capita·yr) for Sofia, and about 580 Mg Cu/yr or 4.7 kg Cu/(capita·yr) for New Haven. Over twice the per capita copper discard rate is observed in New Haven compared to Sofia. Although the Sofia overall total is five times higher, its population is ten times higher, yielding a much lower per capita rate.

**Table 7 Summary of Copper Discard Rates for all Streams in New Haven and Sofia**

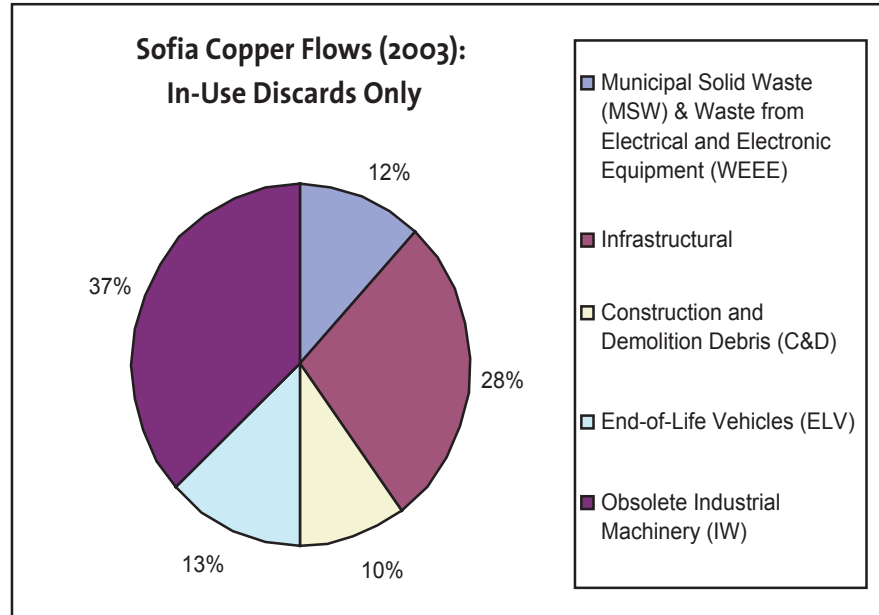
| Waste stream                        | New Haven  |                  | Sofia       |                   |
|-------------------------------------|------------|------------------|-------------|-------------------|
|                                     | Mg Cu/yr   | kgCu/(capita·yr) | Mg Cu/yr    | kg Cu/(capita·yr) |
| MSW & Household and Commercial WEEE | 105        | 0.9              | 291         | 0.2               |
| Infrastructural                     | 68         | 0.5              | 658         | 0.5               |
| C&D                                 | 309        | 2.5              | 229         | 0.2               |
| ELV                                 | 85         | 0.7              | 318         | 0.3               |
| HW                                  | 0          | 0.0              | 0           | 0.0               |
| Obsolete Industrial Machinery (IW)  | 17         | 0.1              | 868         | 0.7               |
| <b>Total Cu</b>                     | <b>584</b> | <b>4.7</b>       | <b>2363</b> | <b>1.9</b>        |

As indicated in Figure 3, about half the discard flow of copper in New Haven is from the C&D stream. This result seems reasonable because building and construction is the largest in-use reservoir of copper (Drakonakis *et al.* 2007). The next most important categories are WEEE at 17% and ELV at 15%. Although infrastructural copper is a large repository, its longer in-use lifetimes relative to WEEE and ELV result in an overall lower amount of copper discarded annually.

**Figure 3 The Percentage Distribution of Copper Discard Flows in New Haven**



Obsolete industrial machinery is responsible for the largest discard flow of copper in Sofia (37% of the overall total) (Figure 4). Infrastructure discards are next, at 28%. It is expected that after the Bulgarian economy undergoes recovery, the amounts of copper coming from these discard streams will decrease. As the standard of living in Sofia increases, it can also be expected that the share of ELV, C&D, and WEEE in the discard stream will increase. At present, those categories comprise about 13%, 10%, and 12% of the overall copper discards.

**Figure 4 The Percentage Distribution of Copper Discard Flows in Sofia**

Even though new scrap does not come from the in-use stage, we were able to quantify new scrap flows as part of this research. It is interesting to point out the significant difference in the per capita prompt scrap generation rates in the two cities. In New Haven, the per capita generation rate is 2.6 kg Cu/yr, while in Sofia it is just 0.5 kg Cu/yr. As a result, the percentage of total copper scrap that is new scrap is about 50% in New Haven, while just 20% in Sofia. The weaker state of the Bulgarian economy compared to the U.S. economy is likely responsible for the difference in magnitudes; there are fewer manufacturing activities that generate prompt scrap in Sofia compared to New Haven. However, the percentage of prompt scrap in total copper scrap collected for recycling in New Haven is lower than the national U.S. average of 81% (CDA 2004). It is unclear why New Haven's proportion of prompt scrap is lower than the national average. The stagnant population growth in the northeastern US relative to other parts of the country may be a factor, as more prompt scrap from new construction and less old scrap from demolitions would occur in high growth areas.

### Copper End-of-life Recovery Rates

Socioeconomic factors are thought to influence the recovery rate of copper for MSW and WEEE in Sofia and New Haven. In New Haven it is officially illegal to dispose of electronics in the regular trash, though small electronics often slip through. The poor recovery of smaller WEEE is one of the contributors to the overall low recovery rate of copper in New Haven. Many of the large electric appliances are efficiently recovered because of the large amount of steel contained in them.

In Sofia, a few thousand scavengers contribute to trash containers being checked hourly for recyclables, where even small electronics with low copper content, such as telephones, are collected. Table 8 contains estimates for Sofia for the copper content in different household WEEE and a comparison of the participation of owners versus scavengers in the recycling process. It was found that not only is all small household WEEE brought for recycling by scavengers, but that more than 50% of the large electrical appliances are abandoned by their owners. By surveying 50 random citizens in Sofia (from different age groups and income levels), it was determined that the lack of appropriate transportation and the low perceived return on the effort to bring a large appliance to a collection site are the main reasons for the high percentage of abandoned large WEEE.

**Table 8 Participation of the Different Actors in Household WEEE Recovery in Sofia**

| Appliance       | Amount of copper per item,<br>kg                        | Brought to collection site by: |               |
|-----------------|---|--------------------------------|---------------|
|                 |   | Owners, %                      | Scavengers, % |
| Refrigerator    | 1.0 – 1.2   | 20                             | 80            |
| Stove           | 0.2 – 0.3   | 50                             | 50            |
| Washing machine | 1.5   | 50                             | 50            |
| Water heater    | 1.0   | 50                             | 50            |
| TV              | 1.0 – in old Soviet models<br>0.2 - 0.3 – in new models | 0                              | 100           |
| Video           | < 0.05  | 0                              | 100           |
| Stereo          | < 0.5   | 0                              | 100           |
| Mixer           | 0   | 0                              | 100           |
| Toaster         | 0   | 0                              | 100           |
| Telephone       | < 0.05  | 0                              | 100           |

The copper recovery rates in the C&D and infrastructural streams are similar in Sofia and in New Haven. In both cities copper coming from these streams is widely recovered.

The 7 % losses in the C&D stream in Sofia can be attributed to copper wires that were laid in the building walls without being placed first in protective tubing. Removing such wires before a building is demolished is very difficult and often even the scavengers at the C&D landfill cannot recover them. Table 9 presents estimates for the reuse and recovery rates for the major C&D sub-streams in Sofia. The percentages indicated as lost are landfilled at a C&D landfill.

In New Haven, losses of copper in C&D can be attributed the difficulty in recovering all electrical and telephone wire during the demolition process, as the smallest gauge wire is often deemed too valueless for recovery.

**Table 9 Reuse and Recovery Rates of Copper in C&D Sub-Streams in Sofia**

| Sub-streams                        | Reuse, % | Recovery, % | Losses, % |
|------------------------------------|----------|-------------|-----------|
| Copper pipes (water, heating, gas) | 1-2      | 96-98       | 1-2       |
| Brass sink and shower faucets      | 2-3      | 95-97       | 1-2       |
| Roof gutters and roof cover sheets | 0        | 99.5        | 0.5       |
| Copper wires                       | 10       | 80          | 10        |

Estimates for the copper end of life recovery rates ( $R_{EOL} = R_s/t$ ), defined as the mass of copper collected for recycling divided by the total amount of discarded copper, are based both on the literature (ICSG 2004) and on personal interviews. The Sofia study relied mainly on personal interviews (with government officials, scrap dealers, construction managers, scavengers, etc.), while the study in New Haven also utilized published data. Naturally, the proportion of copper discards that are recovered could not be established precisely. Ranges with high, low, and best estimates were determined by varying to what extent certain goods might reasonably be recovered. For instance, for C&D in New Haven, the low estimate assumes that only architectural copper, half of the wiring, all plumbing tube, and new clippings in installation are recovered, while the high estimates assumes all copper in a building is recovered. The best estimate arises from our informed assumptions of the most likely recovery, based upon our quantitative and qualitative understanding of the discard management system. The low, high and best estimates by stream for both Sofia and New Haven are presented in Table 10. Using the best estimates, the amount of recovered copper per capita was determined for each of the waste streams. These estimates are presented in Table 11 (rounding error may cause the sum to not exactly match the summation of each waste stream as presented).

**Table 10 Low, high and best estimates for end of life recovery rates in New Haven and Sofia**

| Discard streams                     | Percent in New Haven |                |                | Percent in Sofia |                |                |
|-------------------------------------|----------------------|----------------|----------------|------------------|----------------|----------------|
|                                     | Low estimates        | High estimates | Best estimates | Low estimates    | High estimates | Best estimates |
| MSW & Household and Commercial WEEE | 5                    | 93             | 49             | 98               | 100            | 99             |
| Infrastructural                     | 95                   | 100            | 99             | 98               | 99             | 99             |
| C&D                                 | 77                   | 100            | 95             | 90               | 95             | 93             |
| ELV                                 | 94                   | 95             | 94             | 81               | 100            | 91             |
| Obsolete Industrial Machinery (IW)  | 99                   | 100            | 100            | 99               | 100            | 100            |
| <b>End of life recovery rate</b>    | 69%                  | 98%            | 87%            | 95%              | 99%            | 97%            |

**Table 11 Per capita copper recovery rates in New Haven and Sofia**

| Discard stream                            | New Haven                          |      |                                    | Sofia                              |      |                                    |
|---|------------------------------------|------|------------------------------------|------------------------------------|------|------------------------------------|
|   | kg Cu/<br>(capita·yr)<br>generated | %    | kg Cu/<br>(capita·yr)<br>recovered | kg Cu/<br>(capita·yr)<br>generated | %    | kg Cu/<br>(capita·yr)<br>recovered |
| MSW & Household<br>and Commercial<br>WEEE | 0.9                                | 49%  | 0.4                                | 0.2                                | 99%  | 0.2                                |
| Infrastructural                           | 0.6                                | 99%  | 0.6                                | 0.5                                | 99%  | 0.5                                |
| C&D                                       | 2.5                                | 95%  | 2.4                                | 0.2                                | 93%  | 0.2                                |
| ELV                                       | 0.7                                | 95%  | 0.7                                | 0.3                                | 91%  | 0.2                                |
| HW  | 0.0                                | 0%   | 0                                  | 0.0                                | 0%   | 0.0                                |
| Obsolete Industrial<br>Machinery (IW)     | 0.1                                | 100% | 0.1                                | 0.7                                | 100% | 0.7                                |
| Total Cu                                  | 4.7                                | 87%  | 4.1                                | 2.0                                | 97%  | 1.9                                |

### Summary of Derived Discard Parameters

In Table 12, the results of this study are related to the copper flow diagram of Figure 2 and the recovery rate. We were able to estimate only one of the four parameters identified as of potential interest in the study – the discard flow ( $\delta$ ). Further analysis of the recycling efficiency would allow for the quantification of the overall recycling flow ( $\epsilon$ ), and the overall landfill flow ( $\lambda$ ). As mentioned earlier, recycling efficiency is out of the spatial boundary of the city scale, so only the recovery rate was computed. The discard and recovery flows are larger in Sofia, both because it is a much larger city and because of the substantial technological restructuring that is under way. In contrast, the landfill flow from unrecovered copper is higher in New Haven, a reflection of its significantly lower end of life recovery rate. We were not able to quantify the flow of copper in products being reused within the cities ( $\iota$ ). However, because almost all copper stock in cities is in buildings, infrastructure, or industry (Drakonakis *et al.* 2007), we estimate that the reuse flow is less than 5% of the discard flow, and so derive the values of  $\iota$  given in Table 12.

**Table 12 Derived Copper Discard Parameters**

|                           | Total (Mg Cu/yr) | Per capita (kg Cu/yr) |
|---------------------------|------------------|-----------------------|
| <b>New Haven:</b>         |                  |                       |
| Discard flow ( $\delta$ ) | 580 $\pm$ 150    | 4.7 $\pm$ 1.2         |
| Recovery flow (Rs)        | 510 $\pm$ 120    | 4.1 $\pm$ 0.9         |
| Reuse flow ( $\iota$ )    | < 30             | < 0.1                 |
|                           |                  |                       |
| <b>Sofia:</b>             |                  |                       |
| Discard flow ( $\delta$ ) | 2360 $\pm$ 590   | 1.9 $\pm$ 0.5         |
| Recovery flow (Rs)        | 2290 $\pm$ 570   | 1.8 $\pm$ 0.4         |
| Reuse flow ( $\iota$ )    | < 120            | < 0.2                 |

### Estimating Uncertainty in the Results

The uncertainty in these estimates between New Haven and Sofia is difficult to assess in any quantitative way due to the vast array of methodologies used in the two cities. The New Haven estimates are based mostly on product lifetime estimations combined with data from the New Haven copper stocks study, which aimed at capturing at least 80% of the copper stocks (Drakonakis *et al.* 2007). Therefore, the estimate for the yearly generation rate of copper scrap in New Haven is expected to be at least 80% of the actual copper flows leaving in-use. The copper discard rates in Sofia are based on estimates of the total copper collected for recycling in the city, the percent contribution of each waste stream to that total amount, and on estimates of the copper recovery rates for each of the waste streams. The accuracy of the discard generation rates that are determined are therefore difficult to specify, but are thought to be within 25% of the actual numbers. Though not statistically rigorous, the results of this study do provide orders of magnitude estimates that have not heretofore been made.

## DISCUSSION

Although the results for the individual discard streams are shown in Table 7, it is useful to comment upon them in more detail. For example, the generation rate in the combined MSW and household and commercial WEEE stream is three times higher in New Haven than in Sofia. This finding is consistent with the socioeconomics of the two cities. This difference is expected to decrease in the future due to the anticipated increase in the purchasing power of the population of Bulgaria. This wealth will lead to more electronics and electrical equipment per capita and to shorter lifetimes of the equipment. Although in New Haven some discarded electronics are separately collected and treated, in Bulgaria (as of 2004) most of the WEEE enters the MSW stream and then is recovered by scavengers.

The magnitudes of the copper discards generated per capita in the infrastructure stream are roughly equivalent for both cities. Copper in this stream is mainly used for electrical distribution and telecommunications. Both Sofia and New Haven have had

similar patterns of copper usage for these applications through the years and consequently the per capita outflows from that stream are similar. In both cities the electrical and telephone line infrastructures are well established.

In the C&D stream, the per capita generation in New Haven is over ten times higher. This difference is mostly a result of the different historical usages of copper pipes in the two cities due to the higher income levels in the U.S. In New Haven 85-90% of the water pipes in use are made of copper, where in Sofia the number is in the range 1-3%. Again, this difference is expected to decrease in the future. According to a leading Bulgarian trader of ferrous and non-ferrous metal products, in the next 5-10 years, 20-30% of the newly installed water distribution pipes in Sofia's buildings will be made of copper.

Even though the automobile per person ratio for both cities is almost the same (around 0.4 cars/person), New Haven has a much higher copper discard rate per capita from ELV. The main reason is the high average copper content of American cars (about 20 kg Cu/vehicle), while the Soviet-era cars being decommissioned in Bulgaria contain only about a third as much. Another factor that contributes to this difference is that cars remain in service longer in Bulgaria (an average lifetime of about 15-16 years) than in the US (14 years).

The large difference in the amount of copper scrap coming from obsolete machinery is due to the higher turnover of manufacturing machinery in Sofia as a consequence of the changing economics of Bulgaria. New Haven has already de-industrialized, and little machinery and discard of obsolete machinery remains.

Because recycling of copper is currently predominantly market-driven, the higher overall recovery rate in Sofia can likely be attributed to the relative wealth of the two cities. The average per capita income in Sofia is \$2,958/year versus \$16,393/year in New Haven (year 2000). The price for copper scrap is, however, determined by the global market, and was found to be very similar in the two cities (~\$3.00/kg Cu, year 2005). As economics dictates, collecting copper for recycling will be undertaken until the marginal benefit equals the marginal opportunity cost. Due to the lower labor costs presently in Sofia, this equilibrium is established at a higher recovery rate.

If copper recycling becomes part of a global governmentally-mandated material recovery scheme, then the hourly payment/copper scrap price ratio may not be the determining factor for copper recovery. For example, since 2004 in New Haven, household and commercial electronic waste has been prohibited from landfilling and its proper handling is mandated. This requirement, while apparently not routinely followed, may nonetheless be the main reason for the improved recovery rates of copper in the household and commercial WEEE stream in New Haven.

On the other hand, as Bulgaria is aligning its environmental regulations to the European Union directives and adopting extended producer responsibility for WEEE and ELV, it is expected that the copper recovery rates in Sofia for these streams will continue to be high. However, what will change in Sofia is the driving force behind these high recovery rates – a shift from scavenger-based to centrally managed recycling schemes.



## CONCLUSION

The results in this study highlight the higher throughput rates of copper in cities with higher standards of living. Despite the difference in discard rates, the percent recovery of copper is quite high for both New Haven and Sofia (but higher for Sofia). We hypothesize that because recycling is predominantly market-driven, higher recovery rates will exist in cities where the ratio of hourly wages to copper scrap price is lower.

Although the results of this research are of interest to several constituencies, including the metals industry, recyclers, and policy makers, we are unable to provide an indication to what degree they may be generalized. That is, we do not know to what degree New Haven is representative of a developed city, nor Sofia of a developing one, although we suspect that many of the characteristics of industrial practice and human behavior that we describe are typical of the developed and developing worlds. We anticipate that carrying out a modest additional set of similar studies in other cities would provide sufficient information to paint an increasingly informed picture of local, regional, and global copper discards and fates. When such studies are designed, we suggest that developing countries with strong law enforcement and effective public administration would be more likely to have data that are readily available and reliable.

Notwithstanding the data availability limitations, the copper discard and recycling rates of New Haven, CT and Sofia, Bulgaria have been estimated, both in total and for the different discard streams. We feel the results are probably accurate to 25%, but only further analyses in subsequent locales will provide insights into the error. In any event, the work demonstrates the challenges involved in the accurate determination of in-use stock, discards, and reuse, and demonstrates as well that such determinations are crucial to understanding and predicting the reuse, recycling, and sustainability of copper resources over the long term.



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## WORKS CITED

- Agunwamba, J.C. 2003. Analysis of scavengers' activities and recycling in some cities in Nigeria, *Environmental Management* 32: 116-127.
- Copper Development Association (CDA). 2004. The U.S. copper-base secondary industry and its by-products – 2003, Technical Report, A1309-02/04, p.20, retrieved on June 14, 2005 from [http://www.copper.org/resources/pub\\_list/](http://www.copper.org/resources/pub_list/)
- Drakonakis, K., Rostkowski, K., Rauch, J., Graedel, T.E., Gordon, R.B. (2007). Metal capital sustaining a North American city: iron and copper in New Haven, Connecticut. *Resources Conservation, and Recycling*, vol. 49, issue 4: 406-420.
- International Copper Study Group (ICSG). 2004. Information Circular, End-of-Life Vehicles (ELV), May 2004, ICSG/IC/13, retrieved on July 12, 2005 from <http://www.icsg.org/News/Infocirculars/ICSGInfoCircularELV.pdf>.
- Kesler, S.E., 1994. *Mineral Resources, Economics, and the Environment*, New York: Macmillan.
- Ketlogetswe, C. and T.H. Mothudi. 2005. Botswana's environmental policy on recycling, *Resources, Conservation, and Recycling*, 44: 333-342.
- Li, S., 2002. Junk-buyers as the linkage between waste sources and redemption depots in urban China: the case of Wuhan, *Resources, Conservation, and Recycling*, 36: 319-335.
- Maldonado, C. and S.V. Sethuraman. 1992. *Technological Capability in the Informal Sector: Metal Manufacturing in Developing Countries*, Geneva: International Labour Office.
- Medina, M.. 1997. Informal recycling and collection of solid wastes in developing countries: Issues and opportunities, UNU/IAS Working Paper No. 24, Tokyo: The United Nations University.
- Medina, M. 2000. Scavenger cooperatives in Asia and Latin America, *Resources, Conservation, and Recycling* 31: 51-69.
- Norgate, T.E. 2004. Metal Recycling: An Assessment Using Life Cycle Energy Consumption as a Sustainability Indicator, Report DMR-2616, CSIRO Minerals.
- Quinkertz, R., G. Rombach, D. Liebig. 2001. A scenario to optimise the energy demand of aluminium production depending on the recycling quota, *Resources, Conservation, & Recycling* 33: 217-234.
- Sagar, A. and R.A. Frosch. 1997. Perspective on industrial ecology and its application to a metals-industry ecosystem, *Journal of Cleaner Production* 5: 39-45.
- Sörme, L., B. Bergbäck, and U. Lohm. 2001. Century perspective of heavy metal use in urban areas. *Water, Air and Soil Pollution: Focus* 1: 197-211.
- Spatari, S., M. Bertram, K. Fuse, T.E. Graedel, and H. Rechberger. 2002. The contemporary European copper cycle: 1 year stocks and flows, *Ecological Economics*, 42: 27-42.
- van Beers, D. and T.E. Graedel. 2003. The magnitude and spatial distribution of in-use copper stocks in Cape Town, South Africa. *South African Journal of Science* 99, 61-69.

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