Your scrap, my scrap! The flow of scrap materials through international trade

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Abstract— With increasing international trade of secondary materials it is imperative to start including it in our analysis of recycling systems. The goal of this work is to set a materials-flow based foundation to do so. We provide a method for calculating the flow of scrap[1] materials through an interconnected network of international trade. All analysis is presented through the specific example of copper scrap collected in USA, Germany, and Japan, which are leading generators of copper scrap. Results show how the open-economy form can contrast with a closed-economy one, and how different trade networks of the three countries result in different flows, decay rates, and potential recycling returns.

Index Terms— Copper, recycling, international trade, material flow analysis, MFA.

I. INTRODUCTION

Materials play an important role in the development of society. They provide from infrastructure to keepsakes, while enabling new technologies and opportunities. At the same time their extraction, use, and disposal can cause environmental degradation and a reduction in the availability of non-renewable resources from nature. Recycling can be an effective strategy towards alleviating such growing pressures. By definition, it turns raw materials that would otherwise be waste into valuable resources thereby saving on raw materials, their processing, and avoiding disposal. At the same time, it expands the economy by offering more jobs and increases competitiveness [1]. As a result, in previous years, many countries have adopted recycling, exhibiting an increase in waste recovery and recycling rates. However, the key underlying factor driving this trend is not always the environment and sustainability, but usually economics, and mostly those sectors have seen a strong rise in recycling where the economic benefits are clearly apparent. Such incentives have transformed recycling from a closed-economy form to one with rising prevalence of international trade, taking recycling overseas, where there exists not only a greater demand for secondary materials, but often the cheaper labor costs make recycling less expensive. Figure 1 gives empirical evidence of the rising trade rates for 6 major materials through three decades [2]. Copper scrap trade rate increased by roughly 200% over the period, and has the highest trade rate amongst this set.
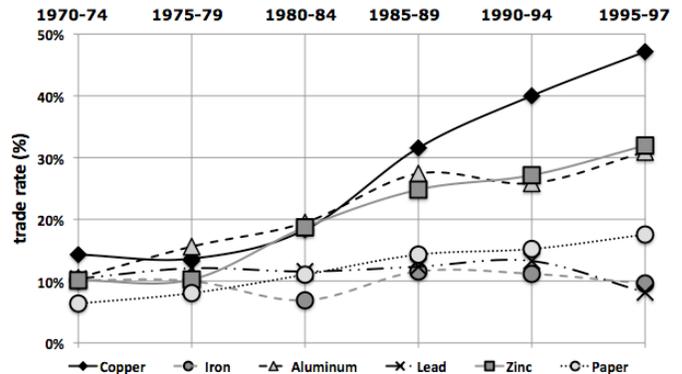

Figure 1: Trends in scrap trade rates for aluminum, lead, iron, copper, zinc, and paper [2].

Thus, recycling, which by intuition is generally considered to be in closed-loop form (scrap replacing raw materials in the same market), has in fact evolved into a complicated network involving multiple nations, usually flowing from developed to developing countries [2]. This trend and significant restructuring of the scrap market imperatively calls for a detailed assessment of combining recycling and international trade.

Previous research on material recycling has seldom accounted for international flows. However, a few studies have made significant contributions. Amongst them is the work by Pieter van Beukering, who empirically illustrates increasing international trade in recycling, with flows from developed to developing countries becoming more common [2]. He has created models and theories explaining these flows along with case studies that discuss the environmental impacts of scrap trade. Work by Eckelman and co-workers [3,4] has also been instrumental in understanding and modeling of such flows. They have used absorbing Markov chains at regional levels to follow recurring material uses and to calculate the number of uses and the technological lifetime before the material is lost. The work presented here has benefited from their analysis and adds to it by zooming to national scales, at which trade decisions are usually made.

The goal of this project is to research the flows of scrap materials through international trade, following step-by-step the materials from collection as scrap, up to final loss to

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[1] 'Scrap' in this paper refers to old scrap generated post-use.

environment[2]. This study exemplifies this analysis by focusing on copper scrap, given its large consumption [5], recyclability [5], and high trade rate [2]. Impacts of international flows in scrap treatment are assessed for the three largest generators of copper scrap – USA, Germany and Japan[3] [6]. Comparisons are made between the individual scrap flows from these countries, and to hypothetical closed-economy forms where scrap is not internationally traded, but instead entirely consumed domestically.

II. METHODOLOGY & DATA SOURCES

The life cycle of collected scrap material includes several sequentially occurring phases (also referred as 'states' here, in the context of material residence) – reprocessing or revival of the scrap material to usable form, use of the material to manufacture products, use of the products, and then end of life at which a material may be recollected or dissipated. From one phase to the next, the material/product needs to be transported, and in this interim the material may witness international trade. Materials can be traded in scrap form or processed form (after the scrap is processed), individually or as a part of a product. In every case this alters its lifecycle because of the changed market conditions. This influences not only the intended life of the material but also subsequent flows and uses that materials, especially those with high recyclability, can provide.

In order to follow the total life flow of copper scrap i.e. including all lifecycles, data on scrap collection rates, and domestic use and trade rates of scrap and processed copper, were obtained for USA, Germany and Japan, as well as for countries to which copper scrap originating in these countries was exported. This data was then assembled in the form of a matrix with elements T_{ij}, the fraction of copper in Phase i that flows to Phase j. We call this the *transition* or *flow* matrix. Phases in different countries were recorded as different matrix entries, thereby allowing inclusion of trade rates within the same matrix. For example, with i = USA scrap collection, and j = China scrap processing, T_{ij} takes into account the fraction of collected USA scrap that flows to China scrap processing facilities. Given an initial distribution 'm' of the material amongst all possible states, the distribution after k transitions is $m*T_{ij}^{k}$. Changes in the transition matrix with subsequent transitions can also be modeled. The final result is a step-by-step distribution of material, copper in this case, across all phases/states, through all life cycles of the material. The model is run until the material is only present in 'lost' or 'dead' states like landfills. Multiplication of flow matrices with energy consumption matrices (or other impact factors) can give the energy consumed through each transition step.

The two key data used are trade rates and recycling efficiencies[4]. Trade rate data was predominantly obtained from

[6-8] and recycling efficiency data from [7, 9-13].

III. RESULTS & DISCUSSIONS

Specific to copper scrap generated in USA, Figure 2 gives the fates as a fraction of total copper scrap collected (gross weight) from 1995-2009 [7]. Trade rates to China have increased close to 5-fold in the last 15 years, with the fraction retained domestically decreasing to less than one-third over the period. In 2007 (before the economy started declining) the fraction exported to China was over 60%, with small fractions also being sent to Canada, South Korea, and few other countries, making the copper scrap export to be over 75% of total collected in USA. Following the copper scrap generated in USA in 2004, Figure 3 gives a schematic representation of the transitions, along with the respective transition rates, recurringly encountered through the lifecycles of the scrap. Only flows, which are 5% or more of the total flows out of a *state,* are modeled independently, while the rest are accounted for cumulatively in the dummy-state 'other countries'. Evidently, the presence of international trade (presented in *dashed lines*) is nowhere close to negligible. The system gets even more complicated when analyzing scrap generated in Germany given the proximity of neighboring member countries of the EU, increasing trade amongst them. For Japan however, the majority of the export of copper is to China, making the system much simpler.
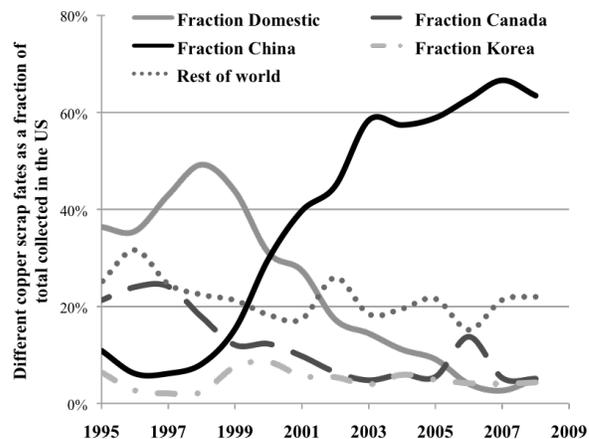

Figure 2: Copper scrap fates as a fraction of total collected in the US [7]. Absolute values used in gross weight.

Using the methodology described, material flows are estimated for copper scrap generated and collected in USA, Germany, and Japan. Fractional distributions between all phases of lifecycles across domestic and export countries are obtained through sequential transition steps. This data is presented in Figure 4. The material states are broadly, but comprehensively classified as 'available' and 'lost'. 'available' refers to states where material is available for future use and has potential to flow to the next phase. 'lost' refers to states from where material usually is not recovered, like landfills or other dissipations. The distributions are plotted with time counted in copper lifecycle lengths. Lifecycle length depends

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[2] "loss to environment" or a "lost" state includes both states where material may be available for recovery and just not recovered (i.e. resting), e.g. landfills, or where material simply cannot be recovered and is lost forever.

[3] For temporal consistency most data of this study correspond to 2004, and so does the order of scrap generators. In recent years, China has grown with its consumption of copper and hence generation/collection of copper scrap [6,7].

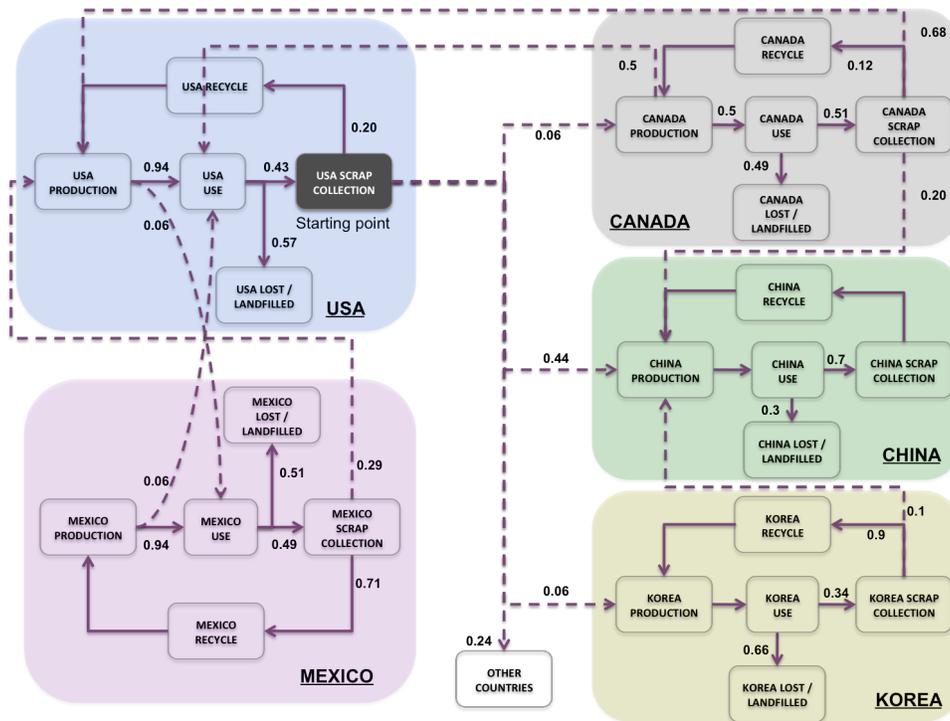[4] Fraction of scrap exiting use that is recollected for recycling

Figure 3: Flow directions and rates of copper scrap collected in USA, through domestic and international use. Solid lines represent domestic flows and dashed lines represent international trade. All numbers represent fraction of state output. Data above and similar data for other countries, has been obtained for the year of 2004.
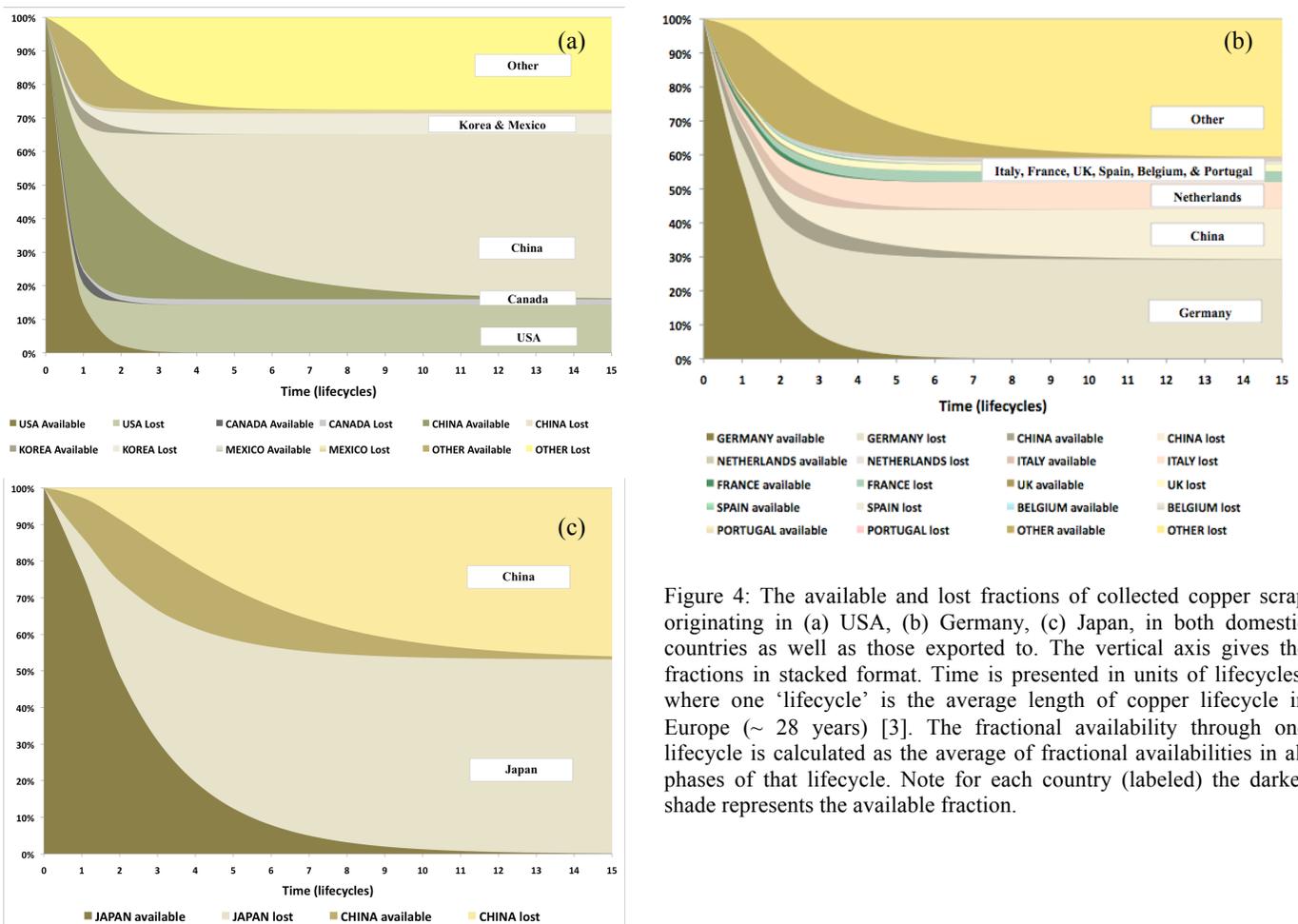

Figure 4: The available and lost fractions of collected copper scrap originating in (a) USA, (b) Germany, (c) Japan, in both domestic countries as well as those exported to. The vertical axis gives the fractions in stacked format. Time is presented in units of lifecycles, where one 'lifecycle' is the average length of copper lifecycle in Europe (~ 28 years) [3]. The fractional availability through one lifecycle is calculated as the average of fractional availabilities in all phases of that lifecycle. Note for each country (labeled) the darker shade represents the available fraction.

on the product mix, use styles and other factors, which can vary from country to country. In this paper one lifecycle is ~ 28 years long which is the average length of one lifecycle of copper in Europe, as well as Asia [3], and assumed to be fixed through subsequent lifecycles.

The results are quite revealing and interestingly different from the common closed-loop perception associated with recycling. Firstly, the large flow of USA copper scrap to China, and the high recovery rate of disposed copper in China [13] are the key factors that make USA copper scrap live through several uses before being lost. The fraction retained in USA is lost within 3 lifecycles, while that flowing to China is available for longer. A decent contribution also comes from the quarter of USA scrap flowing to other countries, which are modeled with global average recovery rates, and in closed-economy form (no international trade). After approximately 10 lifecycles almost all of the USA collected scrap is lost and not available for further use. Copper scrap collected in Germany also becomes unavailable (is lost) after 10 lifecycles. However, compared to USA scrap, German scrap is (re)used domestically at larger fractions, while the rest is distributed in a larger number of countries owing to the proximity of the EU member countries. No export country retains more than 15% of the scrap initially collected over all lifecycles. The third case, Japan, is much simpler, with over 95% of the export copper flowing to China, and thus making the system contain only two countries. High recycling efficiencies of Japan and China make the copper last for ~ 13 life cycles, roughly 30% longer than USA and Germany Scrap. Japan, unlike USA, recycles (over the course of all lifecycles) a majority of its copper scrap domestically as opposed to exporting it.

We can also look at aggregate decay trends of copper scrap, to better compare the effect of international trade on scrap longevity. Figure 5 shows this in the form of total available fractions with time for the three kinds of copper scraps. If we use half-life or 1/10th life (the time after which the available fraction is 0.1) as a benchmark, the longevity of the scrap follows the order Japan > Germany > USA, with the 1/10th life of Japan being roughly 30% more than that of USA. In fact while the Japan decay trend are completely independent, USA decay trend seems to follow Germany in the later lifecycles. The reason for this is that the USA trend is dominated by the recurring use of copper exported to China in the later cycles, which has a similar recycling efficiency to Germany. However, the poorer recycling efficiency of USA shows up in the initial lifecycles leading to a faster loss of available material. Japan on the other hand provides the highest recycling efficiency, with exports to China, which also has a high recycling efficiency, causing the aggregate loss of materials to be much more gradual than the other two.

Figure 5 also plots what the aggregate decay trends would look like if the individual scrap flows followed a closed-economy structure, where all scrap collected was repeatedly recycled in the same country without any international trade. These are shown in *dashed lines*. Given that Japan predominantly exports to China, and that China experiences a lower recycling efficiency, the hypothetical closed-economy form without international trade understandably performs better in its ability to extract more use out of the collected Japan scrap. The total material savings are calculated to be

10% higher for the closed-economy form. For USA however the case is very different. The closed-economy form significantly shortens the life of the copper scrap owing to the lower domestic recycling efficiencies than China, where most of the scrap is exported. International trade has apparently helped increase the amount of service derived per unit of copper scrap collected in USA. In terms of material savings, international trade helps displace 40% more virgin material through the flows compared to the closed-economy recycling structure. In the case of Germany, not only is the export fraction low, most of the countries being exported to have reportedly similar recycling efficiencies and thus the closed and open-economy forms are almost similar.
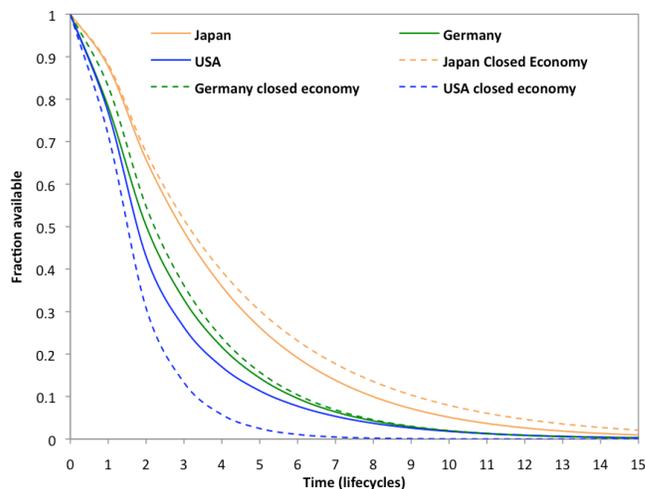

Figure 5: Aggregate decay trends or trends in total fraction available for copper scrap collected in USA, Germany and Japan. The solid lines refer to the flows studied in this paper, and the broken lines refer to the hypothetical cases of closed-economies where all collected scrap is recycled domestically, and none of it is internationally traded.

This model also provides end-point statistics on where the material finally ends up and how much total virgin material is displaced by its journey from initial collection to final loss to the environment. One may also query what the overall energy impacts are, especially on the energy saving often associated with recycling. Figure 6 provides answers to these. 1 kg of scrap collected in USA interestingly displaces only 200g domestically, while it replaces 1.64 kg in China. In total a kg of copper scrap collected in the US helps avoid 2.5 kg of virgin copper production, assuming that the displacement is one to one. For the case of scrap collected in Germany, 1 kg of scrap displaces 3 kg of virgin production in total, roughly the same amount as its analogous closed-economy form. Most of the displacement occurs domestically, in China and in the dummy-state 'other countries'. 1 kg of copper scrap collected in Germany displaces 1.1 kg of copper scrap in Germany, 0.5 kg in China and 1.2 kg in other countries. Of course 'other countries' is a pool of several other countries and thus the displacement on a per country basis is much lower. The simple case of Japan is in fact the most efficient when it comes to virgin displacement. 1 kg of scrap collected in Japan land up displacing close to 3.8 kg of virgin copper. However, this is 10% lower than the closed-economy form. Of these 2.5 kg are displaced in Japan and 1.3 kg in China.

In terms of final distribution of the material, close to 50% of the US collected scrap ends up in China, and only 15% is lost within USA. Scrap collected in Germany is 30% retained domestically while the rest is lost amongst several countries, mainly the EU member states. With scrap collected in Japan, the final distribution is almost an even split between Japan and China, with a little more retained within Japan.

On the energy saving ability of recycling, one can calculate the energy consumption avoided through avoided virgin production, assuming a one-on-one displacement. The cumulative energy demand for primary copper production for the different regions was obtained [14]. The respective total virgin production energy avoided through all uses for copper scrap collected in USA, Germany, and Japan is 232, 132, and 353 MJ per kg copper initially collected. The differences are caused by the different amount of virgin material displacement (Figure 6) and the different virgin product energy consumptions across the respective countries. Interestingly

Germany displaces 20% more virgin material, but ~ 40% lesser total energy as compared to USA.

The last row of Figure 6 provides the distribution for an aggregated collection of copper scrap in USA, Germany, and Japan. Of the total amount collected in these countries, 36% is collected in USA, 37% in Japan, and 27% in Germany. However, the final loss to the environmental is very different, with only 5% in USA, 8% in Germany, and 29% and 40% in Japan and China respectively. A kg of scrap collected across these countries displaces 1.21 kg of virgin copper in China, 0.93 kg in Japan, 0.3 kg in Germany and only 0.08 kg in USA. The total displacement is of 3 kg, and total virgin production energy savings are of 270 MJ.

From an application standpoint, a step-by-step estimated material flow resulting from collected scrap treatment can answer other questions and aid several other analyses as well, like design for recycling, open-loop LCA allocation, etc. However, it is important to realize that the core of the
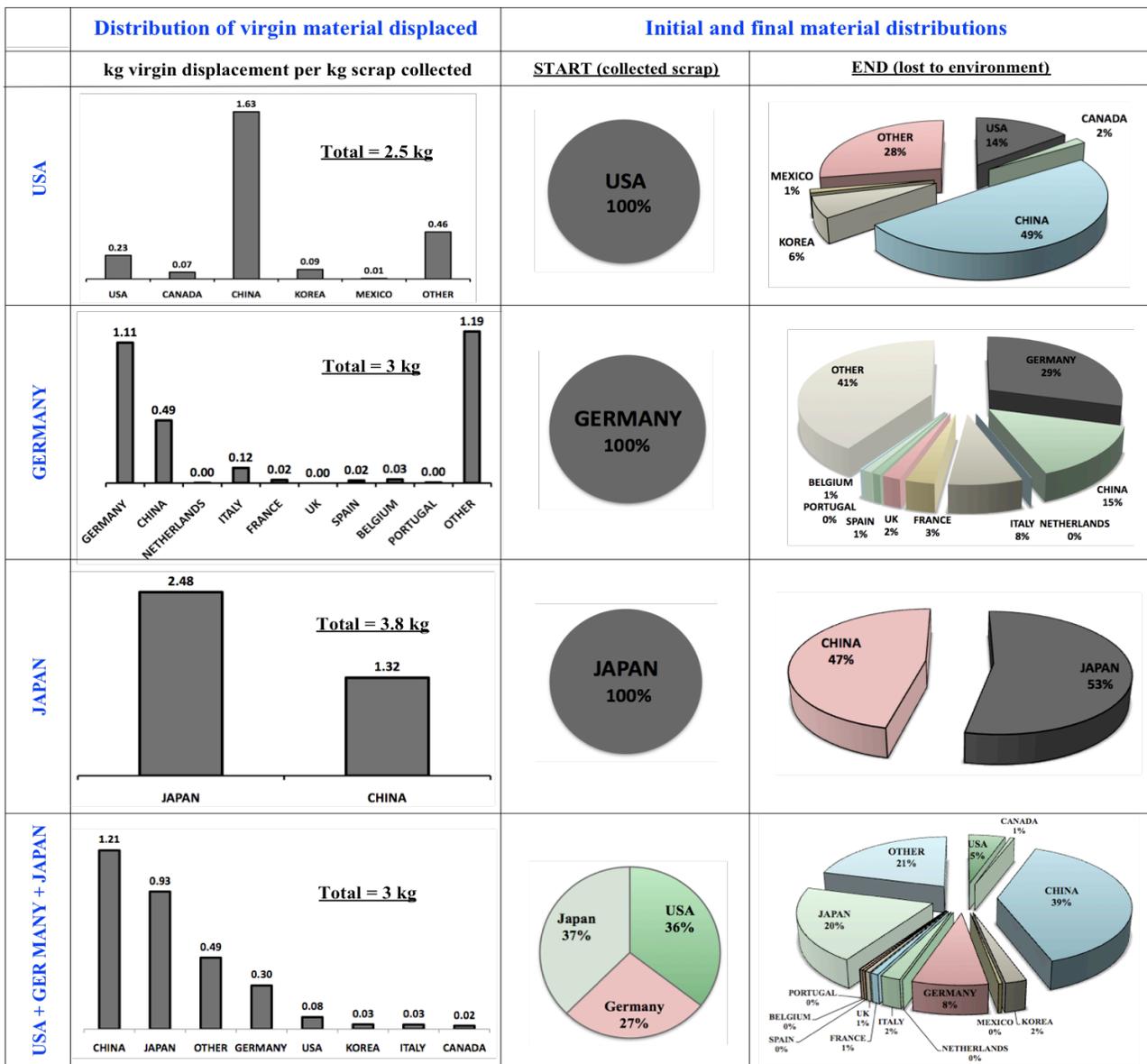

Figure 6: Distribution of (1) virgin copper displacement from scrap recycling, and (2) final scrap loss amongst different countries, for every kg copper scrap initially collected in USA, Germany, and Japan.

modeling relies predominantly on two types of data – trade rates, and scrap collection efficiencies. So one may ask two key follow-up questions that directly affect the results:

1. Why does so much copper scrap flow to China? Is this good or bad compared to using this scrap domestically?

2. Why are the collection efficiencies what they are and how might they change?

Terazono and co-workers [15,16] have closely studied the flow of scrap materials, including copper, in China. Through interviewing 20 companies in China, they realize that the high demand for secondary materials in China is triggered by the relatively higher prices of primary materials. These materials in fact make up for the shortage in domestic supply. They report that the copper scrap imported by China in 2003 could be 2-2.5 times in mass (Cu-content) to that collected domestically. Certainly, a high demand ensures high revenues. However, recycled scrap helps reduce the cost of producing copper as well. Yoshida et. al. mention that through the scrap imported in China is of low grade, its concentration is equivalent to the copper ore, and at the same time does not require processing costs associated with ore refining and recovery [15]. Thus, the economics of copper scrap recycling in China favorably promote import of international scrap. However, from the good/bad perspective, the answer is less clear. Literature contains information on e-waste treatment in China, however that on copper recycling is rather scarce. In Zhejiang Province (where most of the copper scrap went in 2001 [15]) open burning of cables to recover copper has reportedly decreased [16]. However, the exact environmental consequences of recycling copper in China are unknown, given the many small-sized recycling companies. It is also true that exports to China in the past have included some illegal exports that could be both environmentally and socially unfavorable [16]. However, on the positive side, China through its cheap labor is providing a means to utilize low-grade scrap from developed countries where such scrap could be deemed as "waste" from an economic standpoint. The added employment in China is an extra benefit.

The issue on collection efficiencies is also complicated. Disposal to landfills, abandonment due to low economic value, dissipation during use (e.g. fertilizers), hoarding or storage, are only some factors that reduce collection efficiency [10,17]. Estimates are theoretical with the data requirement being huge [10]. Collection rates can increase if the product-mix changes towards more easily recoverable products (including product design changes), and through more efficient collection channels. Copper end-use by itself varies significantly across North America (NA), Europe (EU) and Asia. Buildings and construction (B&C) is the highest use of copper in NA, while electrical infrastructure and electronics are the most common use of copper in Asia. EU is intermediate in terms of these applications [3]. According to ICSG B&C wastes have a collection efficiency of 78%, while industrial electrical equipment and other electric and electronic equipment wastes have a collection efficiency of 65% [10]. A rough estimate of collection efficiency trends can be discerned from trends in end-uses of copper in the different countries. For the case of NA, the 20th century exhibits an increasing use fraction for B&C while diminishing for transport equipment and electrical and electronic uses [18]. Japan shows similar trends with increasing consumption for B&C [11]. On the other hand China is increasingly using its copper for power cable production [19]. However, how these trends will affect recycling efficiencies and thus recycling returns, is hard to guess given the various other technical, political, social and economic factors that dictate material recovery at end-of-life. As a result this work uses a static transition matrix across all lifecycles. Forecasting trade rates and collection rates correctly are not easy tasks, but if possible, can add to a study like this.

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