The contemporary European silver cycle

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Received 21 September 2004; accepted 8 June 2005
Available online 1 August 2005

Abstract

This paper examines the 1-year anthropogenic stocks and flows of silver as it progresses from extraction to final disposal on the European continent. The primary flows of silver include production, fabrication and manufacturing, use, and waste management. A substance flow analysis (SFA) was used to trace the flows and inventory data, and mass balance equations were used to determine the quantity of flows. The results reveal that Europe has a low level of silver mine production (1580 Mg Ag/year) and instead relies on silver imports and the recycling of scrap in production and fabrication.

In the year 1997, Europe imported 1160 Mg Ag of ore concentrate and 2010 Mg Ag of refined silver, and recycled 2750 Mg Ag of new and old scrap. There is a net addition of 3320 Mg Ag/year into silver reservoirs at the use stage. This is the result of a greater amount of silver entering the system from manufacturing than is leaving the system into waste management. The waste flow with the highest content of silver is municipal solid waste, which contains 1180 Mg Ag/year. In total, 62% of all discarded silver is recycled and 38% is sent to landfills. The results of this study and other element and material flow analyses can help guide resource managers, environmental policy makers, and environmental scientists in their efforts to increase material recovery and recycling, address resource sustainability, and ameliorate environmental problems.

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Keywords: Substance flow analysis; Silver; Europe; Stocks and flows; Resource management

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doi:10.1016/j.resconrec.2005.06.003
1. Introduction

Substance flow analyses (SFA) are used to show the flow patterns of an element as it enters and leaves a reservoir such as a country or continent. SFAs can also be used to evaluate the environmental burdens of different processes within the element’s life-cycle. Country and continent level material cycles have been carried out for various substances, including cadmium (Guinée et al., 1999), copper (Spatari et al., 2002), zinc (Gordon et al., 2003), and a number of others. These studies have largely been at the country level, and reveal unique patterns and flows that might not be available from a site-specific study. The data and conclusions from these studies have the potential to affect environmental policies and improve overall resource sustainability.

This paper traces the stocks and flows of silver over a 1-year period as it passes through its life-cycle in the continent of Europe. The goals of the European silver cycle study include the following: to assess the overall flow patterns of the silver cycle; to determine the amount recovered and the amount lost as waste; to establish the amount entering silver reservoirs; and to assess the amount of silver used in Europe. This study is one component of the Stocks and Flows (STAF) project at Yale University’s Center for Industrial Ecology.

2. Methodology

The various flows of silver in and out of the European economy were inventoried using a database modeled after that developed for the African Copper Cycle (Van Beers et al., 2003). Some key definitions of the SFA study are discussed in Table 1. The following sections discuss the methodology used to select a spatial boundary, temporal scale, and materials and processes.

2.1. Spatial boundary

It is necessary to delineate a spatial boundary to see which European countries represent the most significant part of the silver cycle. For the scope of this project, countries were included in the final list if they captured at least 80% of the region’s GDP, GDP per capita, etc.
silver fabrication, silver production, population, or mine production. The final list of countries included Austria, Belgium, Bulgaria, Denmark, Finland, France, Germany, Greece, Italy, Ireland, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, and the United Kingdom. All other European countries were determined to play an insignificant role in the silver cycle. Exceptions to the 80% rule were made due to the political and demographic characteristics of a particular country. For example, even though Yugoslavia qualified because of its GDP, it was not included because of political instability and lack of consistent data during the year of research. Likewise, even though Liechtenstein and Iceland qualified because of a high GDP, they were not included because of low populations and therefore minimal involvement in the silver cycle. Russia will be studied individually as its size and scale merit its own flow analysis. Data for the country selection were retrieved from the World Bank Development Group's website (2002) and from the World Silver Survey (2001).

2.2. Temporal scale

In addition to a spatial boundary, it is also necessary to define the temporal scale. This study chose a 1-year time period for its scope largely because most statistics are reported on a yearly basis. For the European silver cycle, 1997 was selected as a representative sample year. Not only were data essentially complete during 1997, but also the political and economic activity in the region seemed to be at a stable and typical state. If data were not available in 1997, they were extrapolated or estimated based on data between 1994 and 2000 and noted as such in SFA databases.

2.3. Selection of materials and processes

Fig. 1 shows the system boundary of the 1997 European silver cycle. The flows of silver include: production, which includes the sub-processes of mining, milling, flotation, smelting, and refining; fabrication of refined silver and silver alloy into semi-products; manufacturing of silver and silver alloy products; use of silver products; waste management. The following section describes these processes and the transcontinental silver trade in detail.

3. Production

In the production phase, silver ore is processed through mining, milling, and flotation. Mining processes extract silver from the lithosphere, and milling and flotation separate it from its parent materials (usually copper, zinc, or lead) and prepare it as an ore concentrate. Next, the concentrate passes to the smelting and refining sub-processes, which generates refined silver to be sent to fabrication. In addition to domestic mine sources, Europe also imports silver concentrate, and uses new and old scrap from subsequent life-cycle phases. Waste from mining and milling is in the form of tailings; waste from smelting and refining is the form of slag. Production data were obtained from the World Silver Survey (2001) and the CPM Group’s Silver Survey (1997). The British Geological Survey (2000) provided
The mass balance for production processes was determined by Eq. (1), which is defined as follows: $F_{\text{refined silver}}$ represents the total flow of refined silver into the fabrication phase; $F_{\text{mined}}$ the total amount of silver mine production; $F_{\text{import}}$ the total amount of silver imported; $F_{\text{slag}}$ the total amount of silver in slag that is landfilled; $F_{\text{tailings}}$ the total amount of silver in tailings discarded; $F_{\text{scrap}}$ the total amount of silver scrap (new and old) recycled back into production. $i$ is the country index for the $n$ countries.

$$F_{\text{refined silver}} = \sum_{i} F_{\text{mined}}, i(1997) + \sum_{i} F_{\text{import}}, i(1997) - \sum_{i} F_{\text{slag}}, i(1997) - \sum_{i} F_{\text{tailings}}, i(1997) + \sum_{i} F_{\text{scrap}}, i(1997)$$

(1)

4. Fabrication and manufacturing

During the fabrication phase, silver semi-products and silver alloy semi-products (bars, rods, sheets, etc.) are produced from refined silver. In addition to domestic production
Table 2
Production sub-processes, flows, assumptions and approaches and data sources

<table>
<thead>
<tr>
<th>Sub-process</th>
<th>Flow</th>
<th>Assumptions and approaches</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine, mill and flotation</td>
<td>Ore production data</td>
<td>were calculated from an empirical model with concentrate data</td>
<td>Atmaca (2002), Meyer (2002), WSS (2002)</td>
</tr>
<tr>
<td>Concentrate</td>
<td>Country-level concentrate data was taken from literature and summed for all Europe STAF countries</td>
<td>Atmaca (2002), Meyer (2002), WSS (2002)</td>
<td></td>
</tr>
<tr>
<td>Tailings</td>
<td>Tailings were calculated from an empirical model of mining, milling and flotation processes</td>
<td>Atmaca (2002), WSS (2002)</td>
<td></td>
</tr>
<tr>
<td>[5pt] Smelter and refinery</td>
<td>Refined silver total amount of refined silver into fabrication was calculated as the difference between the inputs (domestic and imported concentrate; and the sum of new and old scrap) and slag</td>
<td>Atmaca (2002), Meyer (2002), WSS (2002)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slag was calculated from an empirical model of smelter and refinery sub-processes</td>
<td>Atmaca (2002), WSS (2002)</td>
<td></td>
</tr>
</tbody>
</table>

Sources, refined silver is imported from other countries. The semi-products then proceed to manufacturing, where they are turned into finished silver and silver alloy products. Scrap generated in manufacturing is either recycled back into fabrication or sent to production for further refining. Data sources for these stages of the silver cycle include the World Silver Survey (2001 and 2002) and CPM Group’s Silver Survey (1997). The sub-processes, flows, assumptions and approaches, and data sources for fabrication and manufacturing are outlined in Table 3.

The mass balance for fabrication and manufacturing was determined by Eq. (2), where $F_{\text{silver}}$ and $F_{\text{silver alloy}}$ products represents the total flow of manufactured silver products into use; $F_{\text{refined silver}}$ the total flow of refined silver entering production; $F_{\text{import}}$ the total amount of refined silver and semis imported; $F_{\text{export}}$ the total amount of silver products exported; $F_{\text{scrap output}}$ the total amount of silver scrap sent to production; $F_{\text{scrap input}}$ the total amount of scrap sent to fabrication; $F_{\text{waste}}$ the total amount of silver sent to waste management.

Table 3
Fabrication and manufacturing sub-processes, flows, assumptions and approaches and data sources

<table>
<thead>
<tr>
<th>Sub-process</th>
<th>Flow</th>
<th>Assumptions and approaches</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver fabrication</td>
<td>Silver semi-products</td>
<td>Silver fabrication data were calculated using manufacturing data</td>
<td>WSS (2004 and 2002)</td>
</tr>
<tr>
<td>Silver alloy fabrication</td>
<td>Silver alloy semi-products</td>
<td>Silver fabrication data were calculated using manufacturing data and informed estimates</td>
<td>WSS (2004 and 2002)</td>
</tr>
<tr>
<td>Silver products manufacturing</td>
<td>Finished silver products</td>
<td>Silver manufacturing data were taken from literature and summed for all Europe STAF countries</td>
<td>WSS (2004 and 2002)</td>
</tr>
<tr>
<td>Silver alloy products manufacturing</td>
<td>Finished silver alloy products</td>
<td>Silver alloy manufacturing data was taken from literature and summed for all Europe STAF countries</td>
<td>WSS (2004 and 2002)</td>
</tr>
</tbody>
</table>
5. Use

In the use stage, silver is in the form of a finished product or as a component of products made of diverse materials. The principal uses of silver include electrical and electronics applications, photography, jewelry and silverware, brazing alloys and solders, and coins and metals. Silver is also used in modest quantities in dental fillings, batteries, superconducting wire, and catalysts in the manufacturing of hard plastics (Errecart and Graedel, 2002). Silver’s unique properties include its aesthetics, strength, malleability, electrical conductivity, high reflectance to light, and reactivity (World Silver Survey, 2002). “This versatility means that there are few substitute metals [for silver] in most applications, particularly in high tech uses in which reliability, precision, and safety are paramount” (World Silver Survey, 2002: 54). Data in the use stage was obtained from Roskill (1992) and the World Silver Survey (2001 and 2002). Table 4 shows the percentages of typical silver uses on a global scale.

Table 4
Breakdown of the typical uses of silver

| Industrial applications | 31% |
| Jewelry and silverware  | 27% |
| Photography             | 22% |
| Electrical and electronics | 13% |
| Brazing alloys and solders | 4% |
| Coins and metals        | 3% |


Table 5
Use sub-processes, flows, assumptions and approaches, and data sources

<table>
<thead>
<tr>
<th>Sub-process</th>
<th>Flow</th>
<th>Assumptions and approaches</th>
<th>Data Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use</td>
<td>Silver in use</td>
<td>Silver data was taken from literature, summed for all Europe STAF countries and extrapolated to reflect 1997 values</td>
<td>Roskill (1992)</td>
</tr>
<tr>
<td>Use</td>
<td>Silver entering stock</td>
<td>Calculated by subtracting new silver entering use from the flow of silver entering waste management</td>
<td>Roskill (1992)</td>
</tr>
<tr>
<td>Use</td>
<td>Silver entering waste management</td>
<td>Silver data was taken from literature and summed for all Europe STAF countries. Some informed estimates and extrapolations were made</td>
<td>Roskill (1992), WSS (2001 and 2002)</td>
</tr>
</tbody>
</table>
and Table 5 outlines the sub-processes, flows, data sources, assumptions, and approaches utilized to determine flows in the use stage.

The mass balance of the stocks and other sub-processes in the use stage was determined by Eq. (3), where $F_{use\ stock}$ represents amount of silver remaining in use in 1997; $F_{Ag\ products}$ the total amount of finished silver products out of manufacturing into use; $F_{waste}$ the amount of silver sent to waste management; $F_{scrap}$ is the amount of scrap sent back to fabrication or production.

$$F_{use\ stock} = \sum_{i} F_{Ag\ products, i(1997)} - \sum_{i} F_{Ag\ waste, i(1997)} - \sum_{i} F_{Ag\ scrap, i(1997)}$$

(3)

6. Waste management

For the 1-year flow computation, it is not possible to determine the retirement rate of silver products without knowing the total mass of silver stocks already present in the European continent, together with their residence times and historical flow rates into use. Therefore, in the 1-year budget the total mass of silver retired from use is estimated from annual waste flows that enter the waste management system. Products in Europe are mainly retired within municipal solid waste, waste from electrical and electronic equipment, treated and untreated sewage, industrial waste, and hazardous waste. The sources of silver in each of the waste flows include the following:

- Municipal solid waste (MSW)
  - Circuit boards, old black and white films, photographic prints, dental fillings, non-recycled coins and old silverware, and silver-oxide batteries.
- Waste from electrical and electronic equipment (WEEE)
  - Circuit boards.
- Sewage (S)
  - Photo laboratories, film and print production, medical sewage (dentists and hospitals), galvanic and electroplating work, productions of circuit boards, chemical industry (catalyst production).
- Industrial waste (IW)
  - Photo laboratories, film and print-production, dentists and hospitals.
- Hazardous waste (HW)
  - Silver-oxide batteries and dentists.

In this analysis, IW and HW do not include waste from production (e.g., tailings and slag) and fabrication and manufacturing (e.g., waste from galvanic and electroplating work), as they are treated separately as tailings, slag, and new scrap, respectively. Except for sewage sludge, silver losses to the environment are not treated explicitly in the present work.

Silver enters the waste management system in the waste categories listed above and it may also enter through scrap trade with countries outside of STAF Europe.
The silver discard stream is partitioned in three ways:
- some is recovered and returned to smelters and refineries;
- some is stored in landfills;
- some is sent to an incinerator. A portion of this stream goes to landfill (ash), another portion is lost to the environment and some is recovered and returned to smelters and refineries.

Table 6
Waste generation and silver contents for STAF Europe in 1997

<table>
<thead>
<tr>
<th>Waste category</th>
<th>Waste generation (Gg)</th>
<th>Silver content per unit waste (mg Ag/kg)</th>
<th>Total silver content (Mg Ag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW</td>
<td>165,000(^{a})</td>
<td>7.1(^{b})</td>
<td>1178</td>
</tr>
<tr>
<td>IW</td>
<td>350,000(^{a})</td>
<td>0.9</td>
<td>308</td>
</tr>
<tr>
<td>HW</td>
<td>30,000(^{a})</td>
<td>1.8</td>
<td>52(^{b})</td>
</tr>
<tr>
<td>S (treated) dry weight</td>
<td>770,000(^{a})</td>
<td>12(^{c})</td>
<td>95</td>
</tr>
<tr>
<td>S (untreated) dry weight</td>
<td>3300(^{d})</td>
<td>12(^{c})</td>
<td>32</td>
</tr>
<tr>
<td>WEEE (used/circuit boards)</td>
<td>84(^{e})</td>
<td>2000(^{b})</td>
<td>168</td>
</tr>
<tr>
<td>WEEE (manufacturing)/circuit boards</td>
<td>25</td>
<td>2000(^{b})</td>
<td>50(^{b})</td>
</tr>
<tr>
<td>New scrap (use)</td>
<td>786,000</td>
<td>867(^{f})</td>
<td>687</td>
</tr>
<tr>
<td>New scrap (manufacturing)</td>
<td>1500</td>
<td>50,000–900,000(^{g})</td>
<td>517</td>
</tr>
<tr>
<td>Prompt scrap</td>
<td>300</td>
<td>50,000–900,000(^{g})</td>
<td>148(^{f})</td>
</tr>
<tr>
<td>Total</td>
<td>1,343,519</td>
<td>2.5</td>
<td>3395</td>
</tr>
</tbody>
</table>

Totals may not sum due to rounding.
\(^{a}\) Bertram et al. (2002).
\(^{b}\) The usage of silver in film and photo production (photo laboratories, print shops, hospitals, dentists, veterinarians, radiologists) is about 8 g Ag/(capita year) (Resources Management Agentur, 2000) in STAF Europe except in Romania, Poland, Ireland, Greece and Bulgaria, where 1 g Ag/(capita year) is assumed. 35% of the usage is collected as waste at the source and returned back to the production stage, 20% is collected within the IW stream, 9% enters the sewer system (Resources Management Agentur, 2000) and the rest stays in the developed pictures.
\(^{d}\) Waste from the manufacturing of circuit boards in Germany are estimated around 10,000 Mg/year (Langer, 1994). Using a silver concentration of 0.2% (Siemers and Vost, 1999) this results in a silver waste generation of 20 Mg Ag/year in Germany. Based on the output of 370 Mg Ag/year within circuit boards in Germany a factor of 5.4% was calculated for STAF Europe.
\(^{e}\) Siemens and Vost (1999).
\(^{f}\) A generation of 207 g/(capita year) based on Germany (Langer, 1994; Bertram et al., 2002) was used for STAF Europe.
\(^{g}\) The silver content of MSW varies between 0 and 15 mg Ag/kg (Bekesi, 2002). A concentration of 7.5 mg Ag/kg is assumed for all countries except Romania, Poland, Bulgaria, and Greece and Ireland. For these countries, a concentration of 1 and 3 mg Ag/kg is used because their metal content in MSW is about 1/8 and 3/8 of those in higher developed countries (World Bank, 1999).
\(^{h}\) Annually 26 g/(capita year) of old silver-oxide batteries are discarded in Germany (WEKA, 1999). The collection ratio for batteries is 60% (Swiss Agency for the Environment, 2003). The average silver concentration of silver-oxide batteries is 30%. STAF Europe uses 41 Mg Ag/year in dental applications (Roskill Information Services, 1992). This use results in a silver waste generation of 33 Mg Ag/year (Barron, 2002).
\(^{i}\) Eurostat (2002).
\(^{j}\) Delany (2002).
\(^{k}\) Resources Management Agentur (2000).
\(^{l}\) Ullmann’s Encyclopedia of Industrial Chemistry (2001).
The waste management equation for estimating silver in MSW is shown below:

\[
F_{Ag, MSW} = \text{waste generation rate} \times \text{Ag concentration} \times \text{population}
\]

Units: \([\text{Gg waste/(capita year)}][\text{kg Ag/kg waste stream}][\text{population}]\) (4)

Data on the generation rate of old scrap were taken from the World Silver Survey (2002) and additional waste management data and information were collected from the US Geological Survey (2003). Table 6 shows the annual waste generation in STAF Europe, the silver content of the discard streams, notes, assumptions, and provides a complete list of data sources.

7. Trade

Silver is traded in the form of the following items: concentrate; wrought or unwrought silver; silver and silver alloy semi-products; a finished product (e.g., jewelry); as a component of an assembled product (e.g., electrical and electronics); as scrap. Reported values for scrap trading are assumed to be exclusively old scrap. Import and export data were retrieved from UN Comtrade (2002), a publication from the Statistics Division of United Nations. UN Comtrade reports the value in US$ (and in some cases the gross weight) of traded silver products, and silver as a component of a product. Table 7 indicates products traded, their trade volumes, the silver concentrations in each product, net silver flows, direction of trade, and references.

8. Results and discussion

8.1. Results of production, fabrication and manufacturing, use, and waste management

The detailed production results are shown in Fig. 2. European mines extract approximately 2000 Mg Ag/year from the lithosphere and send 1600 Mg Ag/year to smelting and refining facilities. The remaining silver in tailings is sent to landfills. Approximately, 65% of all European mined silver comes from Poland, 16% from Sweden, 4% from Spain and the remaining 15% from different countries across Europe (World Silver Survey, 2002). Of the material sent to refining and smelting processes, 21% is imported in the form of concentrate, 49% enters in the form of new and old scrap, 29% comes as concentrate from European mined sources, and 1% is silver recovered from slag. Approximately 4 Mg Ag/year of slag is discarded from smelting and refining. Because such a large percentage of inputs come from imports and scrap, there is less slag and tailings waste than might be initially expected from the magnitude of processing flow. After the smelting and refining processes, Europe sends more than 5000 Mg Ag/year of refined silver to fabrication and manufacturing.

Fig. 3 illustrates the results of fabrication and manufacturing processes. Of the refined silver entering fabrication, about 70% comes from domestic production processes, almost all the rest being imported. The fabrication process generates the semi-products (rod, sheets, etc.) that form the input to product manufacturing. Nearly, 30% of the semi-products are in
<table>
<thead>
<tr>
<th>Product</th>
<th>SITC code</th>
<th>Trade volume (Mg/year)</th>
<th>Silver concentration (%)</th>
<th>Silver flow (Mg/year)</th>
<th>Direction of trade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver ores and concentrate</td>
<td>261610</td>
<td></td>
<td></td>
<td></td>
<td>Net import</td>
</tr>
<tr>
<td>In unwrought forms (refined silver)</td>
<td>710691</td>
<td>315 (million US$/year)</td>
<td>157 (US$/kg Ag)</td>
<td>2088</td>
<td>Net import</td>
</tr>
<tr>
<td>Base metals clad with silver, semi-manufactured</td>
<td>7107</td>
<td>679</td>
<td>1</td>
<td>7</td>
<td>Net import</td>
</tr>
<tr>
<td>Base metals, silver, clad with gold, semi-manufactured</td>
<td>7109</td>
<td>75</td>
<td>100</td>
<td>75</td>
<td>Net import</td>
</tr>
<tr>
<td>Silver powder</td>
<td>710610</td>
<td>720</td>
<td>100</td>
<td>720</td>
<td>Net import</td>
</tr>
<tr>
<td>Silver semi-manufactured including gold/platinum plate</td>
<td>710692</td>
<td>−73 (million US$/year)</td>
<td>157 (US$/kg Ag)</td>
<td>−463</td>
<td>Net export</td>
</tr>
<tr>
<td>Silver compounds other than silver nitrate</td>
<td>284529</td>
<td>−42</td>
<td>60</td>
<td>−25</td>
<td>Net export</td>
</tr>
<tr>
<td>Photographic plate, film, paper, photographic paper, board, etc.</td>
<td>3701–3705</td>
<td>−184,500</td>
<td>0.4</td>
<td>−738</td>
<td>Net export</td>
</tr>
<tr>
<td>Glass mirrors</td>
<td>7009</td>
<td>−21,458</td>
<td>0.009</td>
<td>−2</td>
<td>Net export</td>
</tr>
<tr>
<td>Supported catalysts, precious metal based</td>
<td>381512</td>
<td>2402</td>
<td>12</td>
<td>288</td>
<td>Net import</td>
</tr>
<tr>
<td>Silver wares, silver ware plated with precious metal</td>
<td>711411</td>
<td>−43 (million US$/year)</td>
<td>157 (US$/kg Ag)</td>
<td>−275</td>
<td>Net export</td>
</tr>
<tr>
<td>Silver oxide primary cells</td>
<td>850640</td>
<td>634</td>
<td>35</td>
<td>222</td>
<td>Net import</td>
</tr>
<tr>
<td>Electronic printed circuits</td>
<td>853400</td>
<td>6576</td>
<td>0.20</td>
<td>13</td>
<td>Net import</td>
</tr>
<tr>
<td>Parts, electric switches, protectors and connectors</td>
<td>853900</td>
<td>−41,994</td>
<td>0.20</td>
<td>−84</td>
<td>Net export</td>
</tr>
<tr>
<td>Jewelry and parts, silver, including plated silver</td>
<td>711311</td>
<td>−130.5 (million US$/year)</td>
<td>394 (US$/kg Ag)</td>
<td>−311</td>
<td>Net export</td>
</tr>
<tr>
<td>Waste/scrap, precious metals except pure gold/platinum</td>
<td>711290</td>
<td>5769</td>
<td>5</td>
<td>288</td>
<td>Net import</td>
</tr>
</tbody>
</table>

* UN Comtrade (2003).
* World Silver Survey (2002).
* Calculated from “STAF Europe” usage (Ressourcen Management Agentur, 2000) minus manufacturing (World Silver Survey, 2002).
* CBI (2001).
Fig. 2. Silver flows in production. All units are measured in Mg Ag/year (metric tonnes of silver/year).

Fig. 3. Silver flows in Fabrication and Manufacturing. All units are measured in Mg Ag/year (metric tonnes of silver/year). A flow of 178 Mg Ag/year from Fabrication is needed to close the Fabrication budget, but the data are not adequate to specify the destination of that flow.
the form of alloys, including “sterling silver” (which contains about 8% copper for added strength), a variety of brazing alloys, and other specialty semi-products. About 79% of the silver outputs from the manufacturing process are put into use in Europe (again with nearly 30% of the silver in alloy form), 12% comprises silver in exported products (for which data are not adequate to separate into silver and silver alloy forms), and 9% is returned to the production stage in the form of new scrap.

Fig. 4 displays the silver flows in the use stage. The largest use of silver in Europe is jewelry and silverware, which comprises approximately 30% of the total usage. Overall, the largest use for silver on a global scale is in industrial applications, mainly because of silver’s excellent electrical and thermal conductivity (World Silver Survey, 2002). Photography uses represent the second largest silver use in Europe capturing about a quarter of the total. Electrical and electronic uses account for nearly 20% of the total usage; brazing alloys and solders, coins and metals, and other (including dental) applications make up the rest.

From the use stage, some 1800 Mg Ag/year is discarded into waste management, and about 850 Mg Ag/year of silver scrap is sent back to the fabrication and production stages. Approximately 3300 Mg Ag/year is added to in-use stock. Although not shown in Fig. 4, the use stage also sends 32 Mg Ag/year directly to the environment (through runoff and ocean dumping).

Detailed waste management flows are illustrated in Fig. 5. Two-thirds of the silver entering waste management from the use stage is found in the municipal solid waste
Fig. 5. Silver flows in waste management. All units are measured in Mg Ag/year (metric tonnes of silver/year). A flow of 395 Mg Ag/year into waste management is needed to close the budget, but the data are not adequate to specify the origin of that flow.

stream (discarded film, batteries, etc.). Other waste streams contain far less silver content—industrial waste, about 17%; waste from electrical and electronic equipment, about 9%; sewage sludge, about 5%; hazardous waste, about 3%. Nearly 300 Mg Ag/year of old scrap is imported through various streams into the waste management stage. Approximately 240 Mg Ag/year is contained in material that is incinerated. The ash from this process, plus other silver-containing material that is landfilled directly, contain of order 1200 Mg Ag/year. About 70 Mg Ag/year enters the environment through ocean dumping, water, and sediments. The amount of silver discarded into the waste stream is likely to differ among European countries. Countries with higher use levels such as Italy and France will likely add more silver to waste streams than countries with low use levels.

8.2. Results of the comprehensive silver cycle

By combining Figs. 2–5, we generate the comprehensive European silver cycle for 1997, shown in Fig. 6. This section highlights significant findings evident from the aggregate silver cycle.

Overall, there is a high level of silver import throughout the European life-cycle. The only export flow is finished products from manufacturing.

The amount of silver entering use in Europe is much higher than the amount leaving (6010 Mg Ag/year versus 1830 Mg Ag/year); the difference is added to in-use standing stock. This in-use stock will become available for recycling and reuse in the future, as the silver-containing products are discarded.
Europe recycles about 60% of discarded silver and landfills the remainder. The recycling flows into production include as well the new scrap from manufacturing and the old scrap that moves directly from the use phase to the production phase. Together, these flows comprise about 45% of the silver refined in production. Silver in ore native to Europe contains about 35% of the input quantity, imported concentrate the remaining 20%. The overall recycling rate is higher than that for copper (Graedel et al., 2004), zinc (Graedel et al., 2005), and most other metals (Henstock, 1996), a property of the silver cycle that reflects the much higher price of silver and hence the diligence with which it is recovered.

8.3. Discussion

The quantity of silver added to reservoirs in the use stage is about twice the total amount entering landfills. With such a large amount of silver accumulating, it becomes important to manage these stocks for recovery and recycling. This is especially true for a country like Italy, which stores large amounts of silver in in-use stocks compared with other European countries. Additionally, jewelry and silverware should be targeted for recovery and recycling.
because they are relatively easy to recover (compared to other uses) and contain high concentrations of silver.

Because of Europe’s low mine production rate and high import levels, the continent does not experience many of the adverse environmental effects associated with silver mine production. Instead, countries that export silver concentrate to Europe are confronted with related environmental problems, including landscape devastation, waste disposal, and acid mine drainage. The level of environmental degradation that does exist in Europe differs among countries. For example, Poland hosts 60% of the continent’s silver mine production and as a result could account for the majority of Europe’s tailings waste and landscape degradation. Likewise, a country with minimal silver mine production, such as France or Ireland, experiences negligible production-related environmental effects.

9. Analysis of data sources and detail

The reliability of the data presented in this paper varies among different processes and sub-process. The production data are considered reliable because government and trade reports provide dependable and consistent information. Similarly, industry, trade, and government reports provided fabrication and manufacturing stages with reliable data. However, the reliability of the use stage data is not as high. Data on the trade of jewelry, which is a large component of the silver cycle, tend to be incomplete. Waste management data also have a low to medium reliability rating. For some of the waste management flows (e.g., imported waste and waste to environment) there are few data available and empirical models were used to calculate many of the waste flows. The comprehensive silver cycle overall has medium reliability.

Nonetheless, even with data shortages for some sub-processes, it is still possible to develop relatively accurate 1-year substance flow analyses for diverse elements and materials. Collectively, government and industry reports and empirical models can provide researchers with enough information to develop a comprehensive substance flow cycle. With this in mind, more SFA studies are encouraged.

10. Conclusions

The stocks and flows analysis of the European silver cycle bring to light target areas for policy makers to improve the sustainability of silver use. First, to increase recovery and recycling policy makers should target the large silver reservoirs in the use stage, and the large amounts of silver in the municipal solid waste stream. Recycling these flows could lower the demand for virgin material extraction. Second, policy makers should examine ways to encourage increased silver recovery after uses such as photography and electrical and electronic products. Collectively, the waste generated from these uses constitutes a large quantity of potentially recoverable silver. Third, policy makers should examine the environmental performance of export mining countries and individual mines. Because Europe imports large quantities of silver concentrate and refined silver, the continent should ensure that its suppliers have high environmental standards.
Further studies reported elsewhere (Johnson et al., 2005) investigate silver cycles of different continents and specific country-level cycles. Country-level data reveal the major contributors to silver flows, and demonstrate other trends not apparent on continental scales. For future silver cycle studies, it is important to find information about export flows of jewelry, as this information was not complete for the present study. Another aspect worthy of further investigation is a comparison of silver cycles (or other elements) in major export regions (e.g., Latin America) with silver cycles in major import continents (e.g., Europe). This comparison could provide insight on the resource depletion created when there is a high-magnitude use, such as Europe importing large quantities of concentrate and refined silver.

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