Recycling Rates of Aluminum in the United States

Wei-Qiang Chen

Summary

Recycling rates of aluminum are defined in different (sometimes inconsistent) ways and poorly quantified. To address this situation, the definitions and calculation methods of four groups of indicators are specified for the United States: (1) indicators used to measure recycling efficiencies of old aluminum scrap at the end-of-life (EOL) stage, including EOL collection rate (CR), EOL processing rate, EOL recycling rate, and EOL domestic recycling rate; (2) indicators used to compare generation or use of new with old scrap, including new to old scrap ratio, new scrap ratio (NSR), and old scrap ratio; (3) indicators used to compare production or use of primary aluminum with secondary aluminum, including four recycling input rates (RIRs); and (4) indicators used to track the sinks of aluminum metal in the U.S. anthroposphere. I find that the central estimate of EOL CR varies between 38% and 65% in the United States from 1980 to 2009 and shares a relatively similar historical trend with the primary aluminum price. The RIR is shown to be significantly reduced if excluding secondary aluminum produced from new scrap resulting from the relatively high NSR. In 2003, a time when approximately 73% of all of the aluminum produced globally since 1950 was considered to still be “in service,” approximately 68% to 69% of all metallic aluminum that had entered the U.S. anthroposphere since 1900 was still in use: 67% in domestic in-use stock and 1% to 2% exported as scrap. Only 6% to 7% was definitely lost to the environment, although the destination of 25% of the aluminum was unknown. It was either exported as EOL products, was currently hibernating, or was lost during collection.

Keywords:
aluminum recycling
collection rate
industrial ecology
material flow analysis (MFA)
recovery efficiency
substance flow analysis (SFA)

Introduction

Recycling is at the core of the global aluminum industry’s path to sustainable development and of its response to climate change. Compared with the production of primary aluminum, recycling of aluminum products requires as little as 5% to 10% of the energy and emits only 5% to 10% of the greenhouse gas (GHG), because most of the energy required for the production of primary aluminum has been embodied in the metal itself and, consequently, in the scrap (The Global Aluminum Recycling Committee [GARC] 2006; Melo 1999).

The aluminum industry refers to the aluminum cycle as circular; that is, the life cycle of an aluminum product is not the traditional “cradle-to-grave” sequence, but rather a renewable “cradle-to-cradle” cycle. “For most aluminum products, aluminum is not actually consumed during a lifetime, but simply used, and if scrap is processed appropriately, the recycled aluminum can be recycled again and again without any loss of its inherent properties since its atomic structure is not altered during melting”; and “the recycled aluminum can be utilized for almost all aluminum applications, thereby preserving raw materials and making considerable energy savings” (GARC 2006, 6). However, despite these potential benefits, it has been argued that aluminum from end-of-life (EOL) products is not recycled at high rates (McMillan et al. 2010, 2012; Sibley and Butterman 2012).
From the perspective of terminology, recycling rates of aluminum have been defined in different ways in different studies (table 1), and quantitative results are limited. Additionally, although two time-series analyses of aluminum stocks and flows in the United States discussed long-term recycling rates of aluminum (Liu et al. 2011; McMillan et al. 2010), their definitions and calculation methods for aluminum recycling rates, as well as their data on stocks and flows, show substantial variation.

Based on a comprehensive dynamic analysis of aluminum stocks and flows in the United States for the period 1900–2009 (Chen and Graedel 2012), this article aims to achieve the following goals: (1) provide specific definitions of aluminum recycling rates and their calculation methods by comparing and integrating some existing studies (European Aluminum Association [EAA] and Organisation of European Aluminum Refiners and Remelters [OEA] 2004; GARC 2006; Graedel et al. 2011; Martchek 2006); (2) calculate aluminum recycling rates in the United States for the period 1980–2009 and before; (3) explore uncertainty sources of aluminum recycling rate determination at the national level; and (4) discuss the policy implications of defining and quantifying aluminum recycling rates.

### Methodology

#### Scope and System Boundaries

Indicators related to aluminum recycling rates are categorized into four groups (table 2): (1) indicators used to measure recycling efficiencies of aluminum scrap at the EOL stage; (2) indicators used to compare generation or use of new with old scrap; (3) indicators used to compare production or use of primary with secondary aluminum; and (4) indicators used to track the sinks of aluminum in the United States from the systematic and long-term historical perspective. The system analyzed in this study is defined by spatial and temporal boundaries. The spatial system boundary is the geographical border of the United States, whereas the temporal boundary varies depending on the group of indicators and their data availability.

It is necessary to point out that although the study period of the reference study (Chen and Graedel 2012) is 1900–2009, the studied periods in this article are shorter, because the data on stocks and flows for the earlier decades of 1900–2000 tend to have high uncertainties. In particular, for old scrap generation, which is modeled by a product lifetime model (Melo 1999), the
Table 2 Definitions, calculation methods, studied periods, and uncertainty sources of recycling rates of aluminum in this study

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Long name of recycling rates</th>
<th>Short name</th>
<th>Calculation method</th>
<th>Studied period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 a</td>
<td>EOL collection rate</td>
<td>EOL CR</td>
<td>Equation (2)</td>
<td>1980–2009</td>
</tr>
<tr>
<td></td>
<td>EOL processing rate</td>
<td>EOL PR</td>
<td>Equation (3)</td>
<td>1980–2009</td>
</tr>
<tr>
<td></td>
<td>EOL recycling rate</td>
<td>EOL RR</td>
<td>Equation (1) or (4)</td>
<td>1980–2009</td>
</tr>
<tr>
<td></td>
<td>EOL domestic recycling rate</td>
<td>EOL DRR</td>
<td>Equation (5)</td>
<td>1980–2009</td>
</tr>
<tr>
<td>Group 2 b</td>
<td>New to old scrap ratio</td>
<td>NSR</td>
<td>Equation (6)</td>
<td>1946–2009</td>
</tr>
<tr>
<td></td>
<td>New scrap ratio</td>
<td>NSR</td>
<td>Equation (7)</td>
<td>1946–2009</td>
</tr>
<tr>
<td></td>
<td>Old scrap ratio</td>
<td>OSR</td>
<td>Equation (8)</td>
<td>1946–2009</td>
</tr>
<tr>
<td>Group 3 c</td>
<td>Recycling input rate (including net import, including new scrap)</td>
<td>RIR incl NI</td>
<td>Equation (9)</td>
<td>1960–2009</td>
</tr>
<tr>
<td></td>
<td>Recycling input rate (including net import, excluding new scrap)</td>
<td>RIR excl NS</td>
<td>Equation (10)</td>
<td>1960–2009</td>
</tr>
<tr>
<td></td>
<td>Recycling input rate (excluding net import, including new scrap)</td>
<td>RIR excl NI</td>
<td>Equation (11)</td>
<td>1960–2009</td>
</tr>
<tr>
<td></td>
<td>Recycling input rate (excluding net import, excluding new scrap)</td>
<td>RIR excl NI</td>
<td>Equation (12)</td>
<td>1960–2009</td>
</tr>
<tr>
<td>Group 4 d</td>
<td>Percentage of aluminum accumulated in in-use stock</td>
<td>SK in-use</td>
<td>Equation (13)</td>
<td>1980–2009</td>
</tr>
<tr>
<td></td>
<td>Percentage of net export of aluminum scrap</td>
<td>SK export</td>
<td>Equation (14)</td>
<td>1980–2009</td>
</tr>
<tr>
<td></td>
<td>Percentage of aluminum lost to environment</td>
<td>SK loss</td>
<td>Equation (15)</td>
<td>1980–2009</td>
</tr>
<tr>
<td></td>
<td>Percentage of aluminum whose sink is unknown</td>
<td>SK unknown</td>
<td>Equation (16)</td>
<td>1980–2009</td>
</tr>
</tbody>
</table>

aMajor sources of uncertainty for group 1 indicators are: (1) historical statistics on shipments by major market; (2) estimate of aluminum trade embedded in final products; (3) estimate of lifespans of final products in the use stage; (4) estimate of aluminum entering hibernating stock; and (5) estimate of aluminum trade embedded in scrap and EOL products.

bMajor sources of uncertainty for group 2 indicators are: (1) historical statistics on secondary aluminum production from new and old scrap and (2) estimate or modeling of new and old scrap generation.

cMajor sources of uncertainty for group 3 indicators are: (1) historical statistics on secondary aluminum production from new and old scrap and (2) historical statistics on trade of primary aluminum and secondary aluminum.

dSources of uncertainty for group 4 indicators come from all stocks and flows modeling or estimate. Uncertainties for the denominator mainly come from estimate of lifespans of indicators.

Reliability of the modeling results for a certain year depends on the reliability of historical end-use data dating back one to five decades before that year. Because statistics on historical end use are only available after 1960 (The Aluminum Association [AA] 2010), and it is unreasonable to extrapolate them very far into earlier years, only results after 1980 for the first group of indicators are shown.

For the second group of indicators, data on production of secondary aluminum from new and old scrap are available dating back to 1946 (AA 2010). For the third group of indicators, results are estimated back to 1960 as a result of data availability of trade of unwrought aluminum, which is primary or secondary aluminum ingot used for shape casting or wrought processes (AA 2010). Finally, because determination of the fourth group of indicators requires data on all stocks and flows, results on this group of indicators are only calculated for the period 1980–2009, the shortest studied period for the groups of indicators.

Calculation Methods and Uncertainty Sources of Recycling Rates

End-of-Life Collection Rate, Processing Rate, and Recycling Rate

Both new and old aluminum scrap are processed in the recycling chain (figure 1a) consisting of three substages (Boin and Bertram 2005): collection; treatment (or preparation); and smelting (or melting) of scrap. New scrap (preconsumer scrap) is generated during the production and fabrication and manufacturing stages up to the point where the products are sold to final users. Old scrap (obsolete scrap or postconsumer scrap) is the aluminum contained in discarded final products that reach their EOL. Part of the aluminum is lost from the recycling chain in these three substages and is either landfilled or dissipated into the environment (Chen and Shi 2009; Chen et al. 2010; EAA 2008).

According to the EAA and OEA (2004), the GARC (2006), and Graedel and colleagues (2011), recycling rates of aluminum in the recycling chain can be defined in three categories: collection rate (CR); processing rate (PR); and recycling rate (RR). CR is the recovery efficiency of aluminum when collecting new or old scrap, whereas PR is the recovery efficiency of aluminum when preparing scrap for smelting and smelting scrap into secondary aluminum (figure 1a). Sometimes, the preparation of aluminum scrap includes several subprocesses, and PR must be determined for each of them, such as processing rates of aluminum in the recycling chain of EOL vehicles (illustrated by figure 11 in GARC 2006). Theoretically, for a system (e.g., the global system) for which there is no trade in EOL products and scrap, the RR is the product of CR and PR, as calculated by equation (1):

\[
\text{Recycling Rate (RR)} = \text{Collection Rate (CR)} \times \text{Processing Rate (PR)} \quad (1)
\]

Because new scrap is collected almost in its entirety (EAA and OEA 2004), and the PRs for both new and old scrap
have been well discussed by some former studies or could be estimated based on expert interviews or fieldwork (Boin and Bertram 2005; EAA 2008; EAA and OEA 2004; Wang 2011), the biggest challenge exists in determining the CR and RR of old scrap. Therefore, the determination of new scrap RR is ignored in this study, and the PR of old scrap in the processes of scrap preparation and smelting is assumed to be 92% and 95%, respectively (Boin and Bertram 2005; Chen and Graedel 2012; EAA 2008; Wang 2011).

Methods for calculating the end-of-life collection rate (EOL CR), end-of-life processing rate (EOL PR), and end-of-life recycling rate (EOL RR) of old aluminum scrap are illustrated and exemplified by the 2006 cycle (figure 1b) and equations (2), (3), and (4). It is necessary to point out that when calculating
EOL CR and EOL RR at the U.S. national level, I assume that the aluminum embedded in the export of EOL products and old scrap is entirely recycled, that is, losses in scrap preparation and smelting for the exported aluminum are ignored because they take place outside the U.S. boundary. Therefore, equation (4) is slightly different from equation (1). For measuring the ratio of old aluminum scrap finally used by the U.S. domestic market, another indicator, EOL domestic recycling rate (EOL DRR), is developed and is calculated by equation (5):

\[
\text{EOL DRR} = \frac{\text{Domestically Recycled Old Scrap}}{\text{Old Scrap Generation}} = \frac{R_1}{R_0} = \frac{R_2 + T_3 + T_7}{R_0}
\]

In the numerators of equations (2) and (4), domestically recycled old scrap is calculated based on statistics of secondary aluminum production from old scrap and recycling input rates. For EOL CR and EOL RR, uncertainties come from both the numerator and denominator in equations (2) and (4), respectively. In the denominator, because old scrap generation is modeled by the product lifetime model (Chen and Shi 2012; Chen and Graedel 2012; Melo 1999), uncertainties originate from estimates of the lifespans of final products (table 3), deficiencies in statistics on shipments of aluminum products by major end-use market (AA 2010), and estimates of aluminum embedded in the trade of final products (Chen and Graedel 2012). According to the modeling method, the higher the estimate of lifespan mean value of each end use, the bigger the share of aluminum entering end-use sectors with longer lifespan, or the less net import of aluminum embedded in final products, the less old scrap generation will be modeled and the higher EOL CR will be generated. In this study, only the impacts of different estimates of lifespan mean values (table 3) on the EOL CR and EOL RR are quantified, because shipments of aluminum products and trade of aluminum embedded in final products are calculated based on historical statistics.

In the numerators of equations (2) and (4), domestically recycled old scrap is calculated based on statistics of secondary aluminum production from old scrap, as reported by the AA (2010). However, challenges exist in estimating the trade of EOL products and aluminum scrap. It is reported that the United States has been an exporter of EOL products, especially EOL vehicles and waste electrical and electronic equipment (Kahhat and Williams 2012; Fuse et al. 2009), but it is very challenging to estimate the amount of aluminum contained in these exported EOL products because of data unavailability. In addition, although statistics on scrap trade have been reported by the AA (2010), it is difficult to determine the ratio of new to old scrap in the traded scrap. Although some studies (Liu et al. 2011; McMillan et al. 2010) assume that all traded scrap is old scrap, the aluminum industry argued that most of the exported aluminum scrap is old scrap, whereas most of the imported scrap is new scrap (Wang 2011). Therefore, I regard all exported scrap as old scrap and quantify the range of EOL CR and EOL RR by varying the share of old scrap from 0% to 100% in the imported scrap.

New to Old Scrap Ratio or New/Old Scrap Ratio
New to old scrap ratio (NtO SR) was defined by a U.S. Geological Survey (USGS) circular (Plunkert 2005, 16) as “new scrap consumption compared with old scrap consumption, measured in weight and expressed as a percentage of new plus old scrap consumed (e.g., 40:60).” Using data reported as recovery of aluminum metal from new or old scrap by the AA (2010), NtO SR was calculated for the period 1946–2009 according to equation (6). For convenience in showing results, the ratio of new to old scrap can also be presented as new scrap ratio (NSR) or old scrap ratio (OSR), as calculated by equations (7) and (8), respectively.

In combination with recycling input rates, which will be discussed below, NtO SR (or OSR) “reveals the quantity of metal from EOL products used again for metal production and product manufacturing, and enhances understanding of the degree to which the use of scrap from various stages of the aluminum life cycle is occurring” (Graedel et al. 2011, 359). Unlike old scrap, the recycling of new scrap does not contribute to raw material and energy or emissions saving (Reck and Graedel 2012; Rombach et al. 2012). Actually, more new scrap generation may mean less efficiency of aluminum use in the fabrication and manufacturing processes, leading to higher energy use and GHG emissions (Rombach et al. 2012).

Because data for estimating NtO SR in this study are official historical statistics from the AA (2010), it is difficult to estimate the uncertainties. However, Wang (2011) argued that these statistics may not be reasonable and provided another series of data on new and old scrap generation for the period 1980–2009 (AA 2011):

\[
\text{NtO SR} = \frac{\text{Secondary Aluminum from New Scrap}}{\text{Secondary Aluminum from Old Scrap}} = \frac{R_7}{R_4} \quad (6)
\]

Recycling Input Rate
The recycling input rate (RIR) of aluminum is defined as “recycled aluminum produced from traded new scrap and old scrap as a percentage of total aluminum (primary and secondary
Table 3  Mean value (MV) and standard deviation (SD) of lifespan of aluminum-containing products in the use stage

<table>
<thead>
<tr>
<th>Parameters</th>
<th>MV Low</th>
<th>MV Mid</th>
<th>MV High</th>
<th>SD Low</th>
<th>SD Mid</th>
<th>SD High</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trans</td>
<td>12</td>
<td>20</td>
<td>25</td>
<td>0.5</td>
<td>1.5</td>
<td>2.5</td>
<td>(Liu et al. 2011; USDOE, 2011)</td>
</tr>
<tr>
<td>B&amp;C</td>
<td>40</td>
<td>55</td>
<td>70</td>
<td>5.0</td>
<td>10.0</td>
<td>15.0</td>
<td>(USDOE 2012)</td>
</tr>
<tr>
<td>M&amp;E</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>1.0</td>
<td>2.5</td>
<td>4.0</td>
<td>(Bruggink and Marchek 2004; Liu et al. 2011)</td>
</tr>
<tr>
<td>ConDur</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td>(NAHB and BOA Home Equity 2007)</td>
</tr>
<tr>
<td>EE</td>
<td>25</td>
<td>40</td>
<td>50</td>
<td>1.0</td>
<td>2.5</td>
<td>4.0</td>
<td>(Bruggink and Marchek 2004; Liu et al. 2011)</td>
</tr>
<tr>
<td>C&amp;P</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Estimated by this study</td>
</tr>
<tr>
<td>Others</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>0.5</td>
<td>2.0</td>
<td>3.5</td>
<td>(Bruggink and Marchek 2004)</td>
</tr>
</tbody>
</table>

Note: Dash means that data are not available.

Trans = transportation; B&C = building and construction; M&E = machinery and equipment; ConDur = consumer durables; EE = electrical engineering; C&P = containers and packaging.

resources) supplied to fabricators” (GARC 2006, 32). The RIR is identical to recycled content (RC) when the latter is calculated as \( \text{RIR}_{\text{incl NS}} \) by equation (9), where NI is net import and NS is new scrap. However, RC has some shortcomings, as argued by Graedel and colleagues (2011), Reck and Graedel (2012), and Rombach and colleagues (2012): (1) “Lifespans of aluminum-containing products often span several decades, which, in combination with rapid growth in aluminum use, means that recycled aluminum will meet only a modest portion of demand for many years to come” (Reck and Graedel 2012, 690); (2) RC does not distinguish between new and old scrap as input material. A high RC resulting from a high NSR may only mean inefficient material use as well as more energy consumption and GHG emissions in the fabrication and manufacturing processes. Therefore, it is necessary to know the NSR or OSR when using RC as a criterion for recycling performance; and (3) the calculation of RIR is relatively straightforward at the global level, but difficult, if not impossible, at the national level. The reason is that RC of traded unwrought aluminum is not available, which, in turn, makes a precise calculation of RC of the flow of unwrought aluminum entering fabrication impossible.

For the United States, which has been a net importer of unwrought aluminum since 1960 (Chen and Graedel 2012) and for which the OSR was less than 50% in most years during 1946–2009 (refer to the section “New to Old Scrap Ratio and Old Scrap Ratio” below), it is necessary to know quantitatively how the RIR is influenced by the trade of unwrought aluminum and the use of new scrap. For this purpose, three other indicators of RIR were calculated besides RC: (1) RIR including net import of unwrought aluminum, but excluding domestic secondary aluminum produced from new scrap, \( \text{RIR}_{\text{incl NI excl NS}} \) (equation (10)); (2) RIR excluding net import of unwrought aluminum, but including domestic secondary aluminum produced from new scrap, \( \text{RIR}_{\text{excl NI incl NS}} \) (equation (11)); and (3) RIR excluding both net import of unwrought aluminum and domestic secondary aluminum produced from new scrap, \( \text{RIR}_{\text{excl NI excl NS}} \) (equation (12).

Sinks of Unwrought Aluminum Entering the U.S. Anthroposphere

In a seminal study, experts from Alcoa concluded that “about 73% of all of the aluminum ever produced is contained in current transportation, cable, and building ‘product inventory’...
(in service)” (Bruggink and Martchek 2004; Martchek 2006, 3). This finding reminds us of the importance of developing indicators to quantitatively track the sinks of all aluminum metal that has ever been produced or used.

As illustrated by figure 1b, aluminum metal entering the U.S. anthroposphere in any one year consists of four parts:

\[ SK_{j}^{\text{InUse}} = \frac{\text{Cumulative Aluminum Metal Entering U.S. Anthroposphere}}{\sum_{k=1900}^{j} S_{1,k}} = \sum_{k=1900}^{j} F_{1,k} + \sum_{k=1900}^{j} T_{2,k} + \sum_{k=1900}^{j} T_{3,k} + \sum_{k=1900}^{j} T_{4,k} \]  

(13)

\[ SK_{j}^{\text{SEX}} = \frac{\text{Net Export of Scrap}}{\text{Cumulative Aluminum Metal Entering U.S. Anthroposphere}} = \sum_{k=1900}^{j} T_{5,k} + \sum_{k=1900}^{j} T_{7,k} = \sum_{k=1900}^{j} F_{1,k} + \sum_{k=1900}^{j} T_{2,k} + \sum_{k=1900}^{j} T_{3,k} + \sum_{k=1900}^{j} T_{4,k} \]  

(14)

\[ SK_{j}^{\text{Loss}} = \frac{\text{Losses into the Environment}}{\text{Cumulative Aluminum Metal Entering U.S. Anthroposphere}} = \sum_{k=1900}^{j} L_{2,k} + \sum_{k=1900}^{j} L_{4,k} + \sum_{k=1900}^{j} L_{6,k} + \sum_{k=1900}^{j} L_{7,k} + \sum_{k=1900}^{j} L_{8,k} = \sum_{k=1900}^{j} F_{1,k} + \sum_{k=1900}^{j} T_{2,k} + \sum_{k=1900}^{j} T_{3,k} + \sum_{k=1900}^{j} T_{4,k} \]  

(15)

\[ SK_{j}^{\text{Unknown}} = \frac{\text{EOL Export, Hibernating, or Losses during Collection}}{\text{Cumulative Aluminum Metal Entering U.S. Anthroposphere}} = \sum_{k=1900}^{j} S_{2,k} + \sum_{k=1900}^{j} S_{5,k} + \sum_{k=1900}^{j} L_{5,k} = \sum_{k=1900}^{j} F_{1,k} + \sum_{k=1900}^{j} T_{2,k} + \sum_{k=1900}^{j} T_{3,k} + \sum_{k=1900}^{j} T_{4,k} \]  

(16)

domestic production of primary aluminum \((F_{1})\); net import of unwrought aluminum \((T_{1})\); net import of aluminum semifabricated products \((T_{3})\); and net import of aluminum final products\((T_{4})\). Therefore, historical cumulative aluminum metal entering the U.S. anthroposphere in year \(j\) can be quantified by summing these four flows since 1900. Sinks of aluminum metal are divided into four groups: (1) the part still residing in the U.S. domestic in-use stock; (2) the part that has been exported as aluminum scrap, either new or old; (3) the part that has been lost for sure; and (4) an uncertain remainder, which includes possible net export of EOL products, hibernating stock, which is not currently being used but has not yet been collected or discarded (Kapur and Graedel 2006), and losses in the collecting process. The percentage of each of these four sinks in historical cumulative aluminum metal entering the U.S. anthroposphere for year \(j\), \(SK_{j}^{\text{InUse}}, SK_{j}^{\text{SEX}}, SK_{j}^{\text{Loss}},\) and \(SK_{j}^{\text{Unknown}}\) are calculated by equations (13), (14), (15), and (16), respectively.

Note that only aluminum in metal form entering, leaving, or accumulating in the U.S. anthroposphere is treated here. Therefore, aluminum losses from bauxite mining and alumina refining processes are not included in equation (15):

\[ \text{Data Compilation} \]

All data used for this study are developed from our recent article (Chen and Graedel 2012), and details on data collection and compilation have been described in the supporting information of that article. Because results on EOL CR, EOL RR, and sinks are very sensitive to the mean values of lifespans of final products, estimated ranges of lifespan mean values are listed in table 3. These parameters were determined by comparing various data sources, with surveyed-based and U.S.-specific data preferred, when available. It is also necessary to point out that the best estimate of building and construction lifespan is revised from 45 years in our study (Chen and Graedel 2012) to 55 years in this study, because median lifetimes for most commercial buildings are between 50 and 60 years, as reported by
Figure 2 Results for the first group of indicators related to aluminum recycling rates in the United States from 1980 to 2009: (a) the end-of-life collection rate (EOL CR) of old scrap generated from all end-use sectors; (b) the end-of-life recycling rate (EOL RR) of old scrap generated from all end-use sectors; (c) the end-of-life domestic recycling rate (EOL DRR) of old scrap (i.e., not including the recycling of scrap exported to other countries) and its difference from the end-of-life recycling rate; and (d) the EOL CR of used aluminum cans and the comparison of the EOL CRs (central estimate) between including and not including the containers and packaging sector. Uncertainties resulting from both lifespans of final products in the use stage and estimate on old scrap net export are illustrated. Sector-level collection rates for calculating the results illustrated by the line with the square symbols in (a) are assumed according to Martchek (2006) as follows: transportation, 75%; building and construction, 70%; machinery and equipment, 45%; consumer durables, 20%; electrical engineering, 50%; containers and packaging, 60%; others, 20%.

Results and Discussion

End-of-Life Collection Rate and End-of-Life Recycling Rate

EOL CR and EOL RR results are illustrated in figure 2a and 2b, respectively. EOL CR varies between 38% and 65%, with the valley and peak values occurring in 2001 and 2008, respectively. Assuming that the sector-by-sector EOL CRs of old aluminum scrap at the global level assumed by Martchek (2006) apply to the United States, the EOL CR of all old aluminum scrap (the line with the square symbols in figure 2a) calculated according to sector-by-sector old scrap generation increased from 50% in 1980 to 57% in 2009. Obviously, this study’s central estimate of EOL CR for all old aluminum scrap varies around that calculated according to the sector-by-sector EOL CRs. It is also interesting to see that the central estimate of EOL CR shares a relatively similar historical trend with primary aluminum price (figure 3); that is, the EOL CR of aluminum scrap increased when the aluminum price increased and vice versa for most years in the period 1980–2009.

The central estimate of EOL RR for old aluminum scrap varies between 34% and 61% (figure 2b). It evolves in a similar way to, but is approximately 3% to 7% (absolute value) lower than, the central estimate of EOL CR because of the processing losses. EOL DRR, calculated by excluding the net export of old scraps from EOL RR, increased from 28% in 1980 to 49% (peak value) in 1992 and then decreased to 24% (valley
value) in 2009. EOL DRR was always less than EOL RR because the United States was a net exporter of old aluminum scrap from 1980 to 2009. Comparing the “recovery as percent of generation (RPG)” listed in Table 1 with this study’s central estimate of EOL RR shows that the former is much lower than the latter, and there are two reasons for this difference: The U.S. Environmental Protection Agency (USEPA) (2012) (1) did not include the net export of old aluminum scrap and (2) only considered aluminum scrap recovered from containers and packaging (C&P) while having ignored aluminum scrap from other sectors. Therefore, RPG should not only be less than EOL RR, but also smaller than EOL DRR. For example, RPG in 2008 was only 21%, whereas this study’s central estimate of EOL RR and EOL DRR was 61% and 28% for the same year, respectively.

Uncertainties in modeling the EOL CR of old aluminum scrap arise in both the numerator and denominator of equation (2). For the numerator, the range of uncertainties that resulted from uncertainties of old scrap net export is from −6% to 6% (absolute value of collection rate). For the denominator, uncertainties that arose from different estimates of lifespans of final products vary from −20% to 23%. Combining both of these sources of uncertainties, the uncertainty range of EOL CR is from −23% to 30%. Therefore, it is necessary to be cautious in estimating the range of lifespans when conducting dynamic analysis of stocks and flows for aluminum. In addition, it is important to point out that the collected, but exported, EOL products were not included when calculating EOL CR because of data unavailability, and this assumption will inevitably result in the underestimate of EOL CR. Finally, even aluminum that has reached the EOL and is not collected for domestic remelting or export may not be lost, because part of this aluminum may enter hibernating stock and can be available for future recycling. Therefore, the loss rate of aluminum in the collecting process cannot be calculated by subtracting EOL CR from 100%.

Most aluminum-containing final products have a long lifetime, but that is not the case for the C&P sector (especially including aluminum cans). According to the statistics from the AA (2010), sector- or product-level EOL CR could only be estimated for aluminum cans (figure 2d, the light, thin line). “Since the widespread adoption of aluminum beverage cans in the mid-1970s, the total recycling and recovery of aluminum has been largely driven by the collection of used beverage cans (UBCs)” (McMillan et al. 2010, 2608). Therefore, it is important to see how the EOL CR of old aluminum scrap will be changed if the C&P sector, or at least aluminum cans, is excluded. By deducting C&P scrap generation modeled based on the one-year lifespan assumption in this study from $R_1$ and aluminum collected from used cans from $R_2$ in equation (2), EOL CR of old aluminum scrap without the C&P sector (figure 2d, dark thin line) was derived. The result was similar to that when including the C&P sector (figure 2d, thick line). For some years, EOL CR without the C&P sector was even higher than that when including the C&P sector, meaning that EOL CR of the C&P sector might be even lower than the EOL CR for all old aluminum scrap. Note that the EOL CR of aluminum cans, as indicated by the light, thin line in figure 2d, should be similar to, but a little higher than, the EOL CR of the C&P sector, because aluminum entering the C&P sector may also be used for other applications, such as foils backed with paper, which is believed to have very low CR.

It is interesting that figure S4-1a in the supporting information of McMillan and colleagues (2010) and figure S2b in this article share a similar historical evolution of EOL RR without adjustment for aluminum cans. However, there are two differences between these two studies: (1) EOL RR (central estimate) of old aluminum scrap modeled in this study is higher than that modeled by McMillan and colleagues (2010), and (2) the adjustment for aluminum cans significantly changed the EOL RR value of old aluminum scrap in the McMillan and colleagues (2010) article, but not in this study. Reasons for the underestimate of EOL RR in McMillan and colleagues (2010) may be the following: (1) Both import and export of aluminum scrap are assumed to be old scrap, which can underestimate the net export of old scrap because, actually, a majority of imported scrap is new scrap (Wang 2011), and (2) lifespans of final products used by McMillan and colleagues (2010) are shorter than those used in the analysis presented here, especially for building and construction and electrical engineering. For this key parameter, McMillan and colleagues (2010) did not clearly indicate which estimate they used, although they listed lifespans estimated by Melo (1999) and Müller and colleagues (2006). Note that some lifespans from Melo (1999) may be inapplicable for the United States, although they are good estimates for Germany. Note also that the definition and calculation method of recycling rate in the McMillan and colleagues (2010) article is not indicated, and it seems that the overall recycling rate estimated by McMillan and colleagues (2010) is calculated based on the sector-level collection rate of aluminum assumed by Bruggink

![Figure 3](image-url) Comparison between historical evolution of end-of-life (EOL) collection rate (central estimate) of old aluminum scrap and historical evolution of aluminum price in the United States, 1980–2009. Data on aluminum price are from the USGS (2009). Prices are in constant 1998 US$ per metric ton, which are used for avoiding the impact of inflation.
and Martchek (2004). Finally, McMillan and colleagues (2010) only analyzed uncertainties resulting from different lifespan distribution models, which have been shown to be relatively unimportant (Chen and Graedel 2012), while ignoring the impact of different estimates of lifespans on the recycling rates.

**New to Old Scrap Ratio and Old Scrap Ratio**

According to figure 4, approximately 70% to 80% of secondary aluminum was produced from new scrap in the United States for most years in the period 1950–1970. There are two reasons for this result: (1) There was not much old scrap generation in that period because the aluminum in-use stock was still too “young” and small, and (2) the efficiency of material use in the fabrication and manufacturing processes may have been relatively low, which led to high rates of generation of new scrap. From 1970 to the early 1990s, OSR kept increasing because of the rapid growth of secondary aluminum production from old scrap. As illustrated by figure 5b in Chen and Graedel (2012), this rapid growth of secondary aluminum production from old scrap mainly resulted from the rapid growth of old scrap generation in the C&P sector. After the peak (58%) in 1992, OSR decreased until 2006 (35%), although old scrap generation was still increasing (figure 5b in Chen and Graedel 2012), probably because of the similar evolution of aluminum price in that period (figure 3) and the growing export of old scrap after 2000.

If compared with the estimation of Wang (AA 2011; Wang 2011), as illustrated by the thinner solid line in figure 4b, OSR estimated according to the AA (2010) would be underestimated and the gap was increasing after 1992. Reasons for this difference may be as follows: (1) Wang (2011) used data on generation of scrap, whereas the AA (2010) used data on consumption of scrap; because the United States exported increasingly more old scrap after 2000, the gap between old scrap generation and consumption was growing, and (2) new scrap generation may have been overestimated by the AA (2010). Unfortunately, the method of collecting and compiling scrap data has never been reported on by the AA (2010) and I cannot compare it with that of Wang (2011). In addition, Wang (2011) did not describe the ratio of new scrap generated from fabrication processes to that generated from manufacturing processes.

**Recycling Input Rate**

Results on RIRs of aluminum in the United States from 1960 to 2009 are shown in figure 5, and some interesting features can be observed: (1) From 1975 to 2009, RIRs were increasing, meaning that, increasingly, unwrought aluminum used in the United States came from secondary production; (2) RIRs can be significantly reduced (more than 20% after 2000) if secondary aluminum produced from new scrap is excluded; and (3)
uncertainties resulting from different RC estimates of the net import of unwrought aluminum became very significant after 1992, even reaching as high as 38% in 2009.

Because of these differences, it is necessary to be very cautious when talking about RIRs and RC, especially when using them as criteria for recycling performance of green production. It is probably best that, at the national level, all four RIRs and their uncertainties should be calculated and their differences noted, so that people using them can know the advantages and disadvantages of each indicator. When using RIR as a measure for green production, the secondary aluminum produced from new scrap should be excluded because it significantly increases the RIR. Otherwise, inefficient material use of aluminum in the fabrication and manufacturing processes, which results in more new scrap generation, may incorrectly indicate greener production. In addition, the trade of unwrought aluminum should be considered when estimating RIRs, because otherwise RIRs would be overestimated for net importers of primary aluminum. In an extreme case, RIRs without considering trade of unwrought aluminum would be 100% in Japan, a country that has not produced primary aluminum for domestic use since the end of the 1980s (Japan Alumni Association [JAA] 2008). It is also necessary to point out that for countries importing or exporting large amounts of aluminum semifabricated products (figure 1b, $T_3$) and final products (figure 1b, $T_4$), RIRs without considering trade of semifabricated and final products may still not be suitable as criteria for green production or green use of aluminum, because RIRs for aluminum flows entering use (figure 1b, $F_1$ plus $T_4$) are still not quantified.

Sinks of Metallic Aluminum Entering the U.S. Anthroposphere

Results and uncertainties in the distribution of metallic aluminum among the four sinks in the United States from 1980 to 2009 are illustrated in figure 6. According to the central estimate of lifespans of final products, approximately 74% of all metallic aluminum entering the U.S. anthroposphere since 1900 was still residing in the domestic in-use stock in 1980, and 2% was exported (net) as new or old scrap. Only 5% was definitively lost into the environment. The destination of the remaining 20% is unknown. It was either exported as EOL products, residing in hibernating stock, or lost in the collection process. This situation did not significantly change in 2009, with the four sinks accounting for 63%, 3%, 7%, and 27%, respectively.

According to Martchek (2006), approximately 73% of all of the aluminum produced globally since 1950 was still in service in 2003. This study’s finding for the United States in the same year is that approximately 69% of all metallic aluminum that had entered the U.S. anthroposphere since 1900 was very clearly still in service, with 67% in domestic in-use stock and 1% to 2% exported as scrap. The reason that the result here is lower than the global level may be the following: (1) This study includes the aluminum entering the U.S. anthroposphere before 1950, of which the majority may have been lost and (2) the aluminum for which the destination is unknown, which was exported as EOL products, hibernating, or lost during collection, accounted for 25% of all aluminum entering the U.S. anthroposphere in 2003. If only 4% of this aluminum is exported as EOL products to be recycled outside the United States or hibernating for future recycling, this study’s estimate would match the global result very well. In fact, this hidden share may be much more than 4%, meaning that more than 73% of all of the aluminum that ever entered the U.S. anthroposphere was still available for future recycling in 2003.

Uncertainties in the distribution of aluminum among the four sinks result from almost all parameters used for calculating the stocks and flows. Of the parameters, the lifespan of final products in the use stage is particularly sensitive. Basically, the longer the lifespans, the more aluminum is distributed to in-use stock and the less is distributed to the sink of which the aluminum destination is unknown. As illustrated by figure 6b,
the uncertainty range for these two sinks resulting from lifespans is from –17% to 8% and from –8% to 17%, respectively.

Concluding Remarks

By collecting and comparing all relevant studies, this article categorized indicators related to aluminum recycling rates into four groups: (1) indicators used to measure recycling efficiencies of old aluminum scrap at the EOL stage, including EOL CR, EOL PR, EOL RR, and EOL DRR; (2) indicators used to compare generation or use of new scrap with old scrap, including NiO SR, NSR, and OSR; (3) indicators used to compare production or use of primary aluminum with secondary aluminum, including four RIRs (RC is one of the RIRs); and (4) indicators used to track the sinks of aluminum metal in the U.S. anthroposphere from the systematic and long-term historical perspective.

Key findings include the following: (1) The central estimate of EOL CR varied between 38% and 65% in the United States from 1980 to 2009 and shares a relatively similar historical trend with primary aluminum price; (2) RIRs can be significantly reduced if excluding secondary aluminum produced from new scrap resulting from the relatively high NSR, and uncertainties of RIRs resulting from different RC estimates of unwrought aluminum trade are rather high; (3) in 2003, approximately 68% to 69% of all metallic aluminum that had entered the U.S. anthroposphere since 1900 was still in use, with 67% in domestic in-use stock and 1% to 2% exported as scrap; only 6% to 7% was definitely lost to the environment; the destination of 25% of the aluminum was unknown. It was either exported as EOL products, currently hibernating, or lost during collection.

Indicators related to recycling rates can be used as critical criteria for assessing recycling performance and green production/use of aluminum, especially when compared to other metals. However, it is important to pay attention to the following points in order not to misuse or be misled by recycling rates that are available in reports or articles: (1) which indicator is concerned and how it is calculated; (2) the advantages and disadvantages of each indicator; (3) sources and ranges of uncertainties; and (4) the necessity of combining some indicators in some situations. Despite this comprehensive analysis, some important issues remain to be explored in more detail: (1) more-detailed and specific analysis on aluminum exported as EOL products, hibernating, and lost in the collection process; (2) more-detailed analysis of EOL collection or recycling rate at the sector or product level; (3) the method of assessing and avoiding quality loss (downcycling) of aluminum in the recycling process; and (4) the distribution and composition of aluminum in the in-use stock and their impacts on the recycling efficiency and usability of future EOL scrap.

Acknowledgements

The research was funded by the Aluminum Association. The author gratefully acknowledges Mr. Marshall Jinlong Wang, Mr. Nicholas A. Adams, and Mr. Chuck Johnson for providing useful data and other information. The author is indebted to Mr. Reid Lifset, Dr. Barbara Reck, Edward Gordon, and the two anonymous reviewers for their helpful comments. Finally, the author expresses special thanks to Professor Thomas Graedel for his constructive guidance, kind support, and language revision. The opinions expressed here are only those of the author and do not necessarily reflect those of the Aluminum Association.

Note

1. Please note that Graedel and colleagues (2011) defines collection rate, processing rate, and recycling rate only for EOL scrap and names them as old scrap collection rate, recycling process efficiency rate, and EOL-RR, respectively. In addition, GARC (2006) defined an indicator, overall recycling efficiency rate, as “recycled aluminum produced from traded new scrap and old scrap as a percentage of aluminum available from new and old scrap sources.”

References


**About the Author**

Wei-Qiang Chen is an associate research scientist at the Yale Center for Industrial Ecology in New Haven, CT, USA.