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Global warming potential of the circular economy of aluminium: the role of old scrap recycling

Abstract: For decades, aluminium recycling was a regional concern traditionally concentrated in the regions with high aluminium demand and a well-organized aluminium recycling industry. Today, however, aluminium scrap is a global raw material commodity. This change has increased the need to analyze the flows of aluminium scrap, as well as to determine the environmental consequences from aluminium recycling. The objective of this work is to determine the environmental consequences of the old scrap aluminium collection for recycling, considering the market interactions. The study focused on Spain as a representative country for Europe. We integrate material flow analysis (MFA) with consequential life cycle assessment (CLCA) in order to determine the most likely destination for the old scrap and the most likely corresponding process affected. Based on this analysis, it is possible to project some scenarios and to quantify the environmental impacts (generated and avoided) associated with aluminium recycling within a global market. From the MFA results, we projected that the demand for aluminium products will be met mainly with an increase in primary aluminium imports, and the excess of old scrap not used in Spain will be exported in future years, mainly to Asia. Depending on the marginal source of primary aluminium considered, the greenhouse gases (GHG) emission estimates varied between -17,088 kg of CO_2 eq. t^{-1} of old scrap collected to -10,305 of CO_2 eq. t^{-1} of old scrap collected for the global or local scenario, respectively. More GHG emissions are avoided with an increase in export flows, but the export of old scrap should be considered as the loss of a key resource, and in the long term, it will also affect the semifinished products industry. Mapping the flows of raw materials and waste, as well as quantifying the environmental impacts derived from recycling, has become an essential prerequisite to consistent development from a linear towards a circular economy.

KEYWORDS: dynamic material flow analysis, consequential life cycle assessment, greenhouse gases, aluminium packaging, Spain

1. INTRODUCTION

For decades, aluminium recycling was a regional concern, traditionally concentrated in regions with high aluminium demand and a well-organized aluminium recycling industry. Today, however, aluminium scrap is a global raw material commodity (EAA, 2006a). In fact, national or regional markets for raw materials, intermediate products, and final products have become increasingly interconnected in a globalizing world, creating more complexity in the supply chain (Liu and Müller, 2013). Several documents have been presented recently (EC, 2012a; EC, 2012b; NPSCS, 2008) to promote Circular Economies (CE) by encouraging recycling as a material independence strategy for green economic development and the reinforcement of local markets. Nevertheless, the first step in determining the potential environmental gains resulting from achieving those objectives is to map properly the material flows along the whole production chain in order to assess the flows and stocks and to establish past trends to project alternative trade patterns. In the case of aluminium, studies were recently published assessing aluminium flows for the United States (Chen and Graedel, 2012), China (Chen and Shi, 2012), and Italy (Ciacci et al., 2013) and also at the global scale (Cullen and Allwood, 2013; Liu and Müller, 2013). All these studies assessed flows and stocks using material flow analysis (MFA), and all of them also noted the need for further environmental studies in order to evaluate the impacts of the aluminium industry.

There is a clear need for studies considering how recycling fits into the bigger economic picture (Gardner, 2013), but studies calculating the environmental impacts derived from the international trade are also essential because increasing trade means increasing transport, logistics and emissions (Liu and Müller, 2013). However, massive international trade requires life-cycle thinking and a global perspective to take into account burden shifting across borders (EEA, 2012). In this sense, consequential life cycle assessment (CLCA) seems to be an effective methodological framework to address the environmental impacts of international industries because it provides a modeling approach that seeks to describe the consequences of decisions when processes are linked via market mechanisms (Weidema, 2009) and allows the limits of the system to be expanded beyond national boundaries. Nevertheless, the CLCA approach applied to quantifying the impact of recycling presents two challenges. First, the process affected by recycling (i.e., raw primary aluminium production or other process) must be identified, and second, the most sensitive technology in the market to a change in demand must be determined (Weidema, 2009). Both identifications depend on the market trend and delimitation. Thus, to quantify recycling through the CLCA methodology, it is necessary to conduct in-depth analysis of changes in the dynamic of supply and demand of material flows. Therefore, because MFA studies require complementary studies of CLCA to assess the environmental impacts, while at the same time, the CLCA needs the material information provided by the MFA studies; the integration of both methodologies is a good strategy to assess the material flows and environmental impacts of recycling within trade interactions.

In this paper, we evaluate the environmental performance associated with an increase of old aluminium scrap collection in Spain for recycling by integrating a dynamic MFA model with a CLCA in order to evaluate the interactions of recycling markets. MFA traces material flows both along technological life cycles and across national boundaries, allowing the most-probable destinies of the old scrap collected in Spain for recycling are determined. CLCA calculates the GHG consequences of recycling related to marginal (product systems) displacements according to local markets and global market considerations. Aluminium scrap is categorized as new and old, representing pre- or post-consumption scrap, respectively; new scrap is nearly 100% recycled either inside a plant or directly by a remelter. We focus on old scrap, therefore, because it is the key issue in recycling and scrap supply (JRC, 2007). Spain was selected because it is the first exporter of aluminium scrap in the European Union (EU) to non EU-countries (Liu and Müller, 2013; EAA, 2012b), and in a previous study, it was detected that there is no study quantifying the GHG emissions due to aluminium old scrap recycling for Spain (Sevigné et al., 2013). Finally, the present study focuses on GHG emissions because the world's aluminium industry contributes approximately 1% of the total anthropogenic GHG emissions (JRC, 2007; Menzie et al., 2010), but it has been reported that recycling of aluminium products requires as little as 5% of the energy and emits only 5% of the greenhouse gas (GHG) of primary production (IAI, 2009).

2. MATERIALS AND METHODS

The methodology proposed in this study consists of two steps. First, a dynamic MFA is conducted in order to monitor trends and changes in the dynamics of raw materials, products and waste, and second, MFA results are integrated into the consequential life cycle inventory (LCI) modeling to project the cause and effect relationships over the economy to quantify the GHG emissions associated with recycling. In the following sections, the methodologies used for the quantifications of flows and stocks (2.1) and for the quantification of GHG emissions (2.2) are explained.

2.1. Dynamic Material Flow Analysis (MFA)

We have applied a dynamic MFA in Spain for 15 years to obtain not only a picture at a specific time but also an overview of the evolution in the recent past of the whole cycle of aluminium to determine changes and trends in raw materials and waste markets and to observe the influence of the accumulated stock; altogether, this information can be useful to anticipate scenarios in the near future. The aluminium life cycle is divided into the following nine processes: bauxite mining [A], alumina production [B], primary aluminium production [C], secondary aluminium production [D], ingot cast production [E], semifinished products fabrication [F], finished products manufacturing [G], use [H] and waste management [I]. Every life cycle process produces aluminium-containing products (ACP) classified as: bauxite (a); alumina (b); primary aluminium (c); secondary aluminium (d); ingot (e); semifinished products (f); finished products (g); end of life products (h); old scrap (i) and new scrap (j). Some of the ACPs are also classified in several subtypes. In the Appendix A, Figure A.1 summarizes graphically the process and flows, while table A.1 summarizes the definitions associated with the ACPs considered in this study.

2.1.1. Accounting methods for flows and stocks

There are several flows associated with each life cycle process, and except for the use process, the total input of each process, consisting of flows from previous life processes and imports, should be equal to the total output, comprising flows to the next life process, loss and exports. Figure 1 summarizes the mass balance, where LP= Life Processes; i= indicator for life processes; j=indicator for the studied years; INPUT= ACP demanded by life process i in year j; production=ACP produced in life process i in year j; Loss=ACP discarded from life process i in year j; Import= ACP imports generated from life process i in year j; Export= ACP exports generated from life process i in year j; consumption=ACP consumed from life process i in year j.

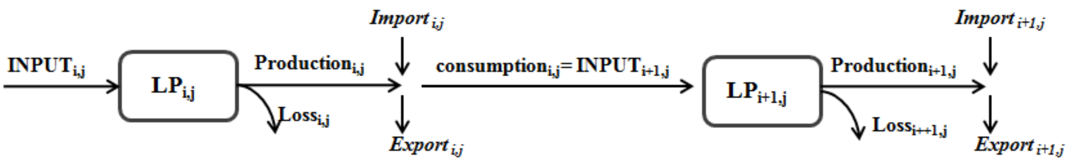

Figure 1: Schematic diagram of mass balance for each LP

Each flow is calculated in three ways; it is calculated directly based on statistics, calculated by combining statistics with coefficients and deduced using the mass balance. Details on data collection and sources and explanations of assumptions, as well as stock calculations, are given in the Appendix A.

2.2. Consequential Life Cycle Assessment (CLCA)

Recycling has been the subject of debate in the field of aluminium LCAs, and many approaches have been proposed to evaluate its impact (Liu and Müller, 2012), but the debate has become polarized (Dubreil et al., 2010). Recent publications from the aluminium industry (EAA, 2007; Atherton 2007) recommend using the end-of life approach to credit the environmental benefits resulting from recycling by accounting for the avoided primary production (Atherton 2007). Conversely, some authors have noted that the recycled content approach is more appropriate because the old scrap can only be reintroduced into the production chain for cast alloys, so it is not clear that primary production is avoided (McMillan et al., 2012; Blomberg and Söderholm, 2009). In this work, however, the results of the MFA have allowed observation of the dynamics of supply and demand of old scrap to and from Spain, and we observed that, in recent years, the increase in old scrap collection in Spain has been associated with an increase of export flows because demand has decreased. Thus, the use of collected old scrap will not affect the amount of old scrap for recycling. Additionally, the price elasticity of the old scrap supply is low or inelastic (Frees, 2008; Blomberg and Söderholm, 2009). For both these reasons, we decided that primary aluminium should be credited by recycling.

The second key issue in consequential LCI modeling is the identification of the affected technology, also called the marginal technology (Weidema, 2009). This means determining which type of primary production is most sensitive to the supply and demand dynamic for primary aluminium, which will also be affected by recycling. The production of primary aluminium can be divided into three main stages: bauxite mining, production of alumina and aluminium smelter (electrolysis), and the geographical locations of these technologies are not necessary in the same country as the studied system (i.e., Spain) (Schmidt, 2012). In this regard, Schmidt and Thrane identified the marginal supply of primary aluminium and stated that in the long term, because aluminium production is assumed to continue to increase and the aluminium market is global, the marginal suppliers are assumed to be the most competitive (Schmidt and Thrane, 2009) in the global market. Their study concluded by analyzing different possibilities, the most likely of which being the scenario in which the majority of bauxite mining is distributed between in China, Australia and Brazil, alumina marginal production is also dominated by China, Australia and Brazil, and smelting and casting marginal production will be situated in China, Russia, and the Middle East (for more details on this identification, please see Schmidt and Thrane, 2009).

In this paper, the production of primary aluminium identified by Schmidt and Thrane (Schmidt and Thrane, 2009) is selected as the global marginal primary aluminium production. Thus, we have defined scenario A-global, a global model of the aluminium market in which every additional ton of old scrap collected in Spain for recycling will avoid a corresponding amount of global marginal primary aluminium production. There remain, however, significant uncertainties associated with this finding. In addition, Spain is also a primary aluminium producer, so it is possible that the old scrap collected in Spain for recycling will avoid the need for the production of primary aluminium in Spain. We defined this alternative as scenario B-local. Nevertheless, there is no bauxite mining in Spain, and the MFA has revealed that during 1995-2010, Spain's main imports of bauxite were from Guinea (datacomex, 2013), a trend that will most likely continue in future years. However, there is no quality data on bauxite mining in Guinea, so the identified marginal mix is considered as the global marginal bauxite producer with an average transport of bauxite from Guinea to Spain (around 5,000 km).

For this study, the system limits have been expanded to include the export of old scrap, its recycling process and the avoided production related to recycling. In this sense, we used export data from 2010 (i.e., percentages and destinations in Europe and China), and we assumed that international recycling will avoid global marginal primary aluminium production, as this scrap is traded in a global market.

In summary, scenario A-global assumes that recycling conducted in Spain and also internationally would avoid marginal global primary aluminium production, while scenario B-local assumes that recycling in Spain would avoid Spanish primary aluminium production, but international recycling would avoid marginal global primary aluminium production. Figure 2 summarizes graphically both scenarios, and detailed information and explanations of the data and calculations are provided in the Appendix B.

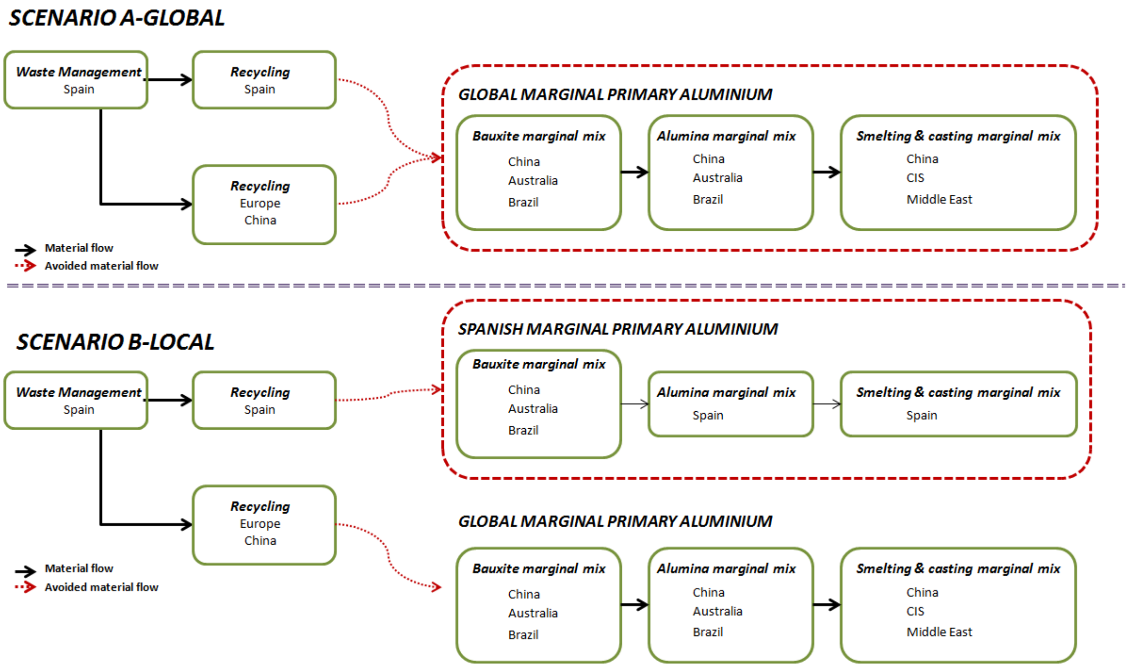

Figure 2: Global marginal primary aluminium production and Spanish marginal primary aluminium production

3. RESULTS

3.1. Dynamic MFA of aluminium flows and stocks from 1995 to 2010

3.1.1. Domestic production and consumption of aluminium products

In figure 3, production and consumption of alumina, primary aluminium and secondary aluminium in Spain from 1995 to 2010 are shown. Because there is no bauxite suitable for alumina production in Spain, its consumption is not shown in the figure. The production of alumina is variable, decreasing by 8.1% from 1995 until 2002 and increasing by 88.5% from 2002 until 2007, with another decrease of 36.8% from 2007 until 2010. However, during this period, the consumption of alumina remained stable at approximately 400,000 (tons of aluminium content per year), parallel to primary aluminium consumption. Between 1995 and 2010 secondary aluminium production increased considerably, with an important increase in 2002, when production increased from 200,000 tons to more than 600,000 tons. In fact, until 2002, the production of primary aluminium was twice that of secondary aluminium, while from 2005 the production of secondary aluminium was twice that of primary aluminium. Consumption of secondary aluminium was higher than production during the entire study period.

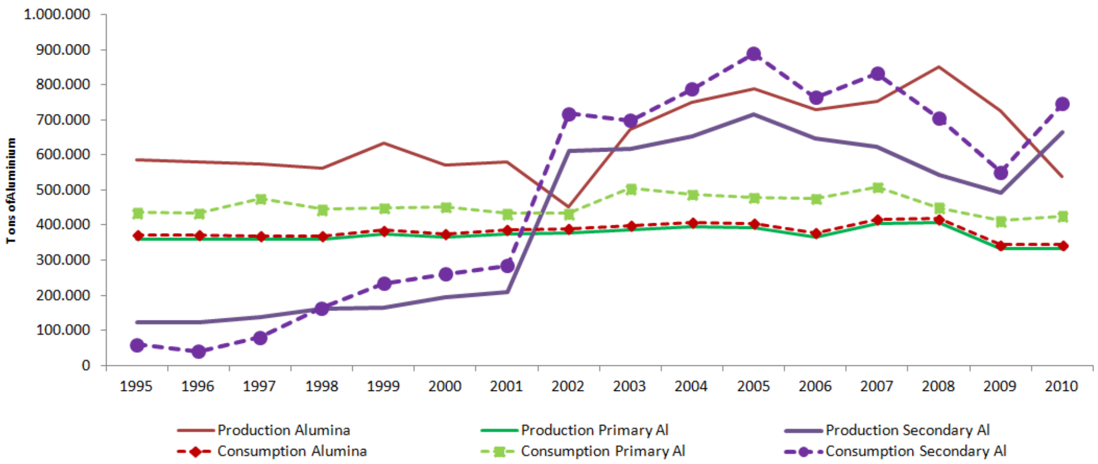

Figure 3: Production and consumption of alumina, primary aluminium and secondary aluminium expressed in tons from 1995 to 2010 for Spain

Aluminium enters semifinished product mainly in the form of aluminium alloys, which are divided into wrought alloys, which generally comprise rolled products, extruded products and other fabricated products, and casting alloys. In this study, the semifinished products were classified by production method into rolling, extrusion, shape casting and others (see Figure 4), and the final products were classified into 5 end-use markets in building, transport, packaging, engineering and others (see Figure 5).

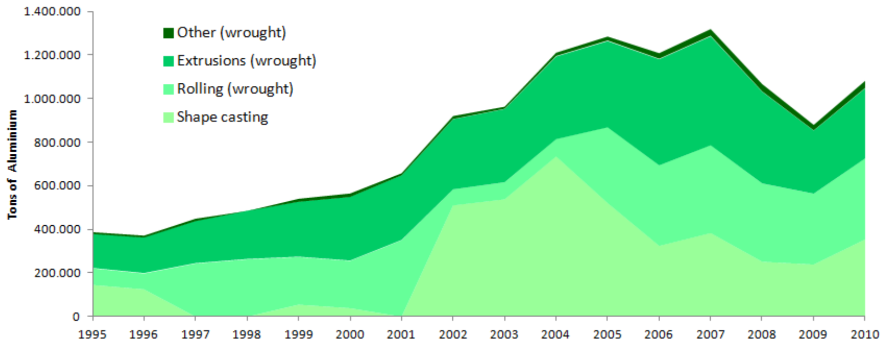

Figure 4: Production of semifinished products expressed in tons from 1995 to 2010 for Spain

Figure 4 shows that the total amount of semifinished product increased more or less continuously until 2007 and decreased after 2009. Wrought products dominated the production of semifinished products until 2001, but in 2002, the production of shape cast products increased considerably. In general, most of the shape casting is used for the transport sector (Cullen and Allwood, 2013; Mathieux and Brissaud, 2013; Boin and Betram, 2006), and it is estimated that the net weight of aluminium in an average vehicle steadily increased by 15% from 1993 to 2003 (EAA, 2006b). Figure 5 shows that the production of aluminium products for transport has also increased from 2002, possibly explaining the increase in shape casting previously observed. The building and engineering sectors also increased their production from 2002 to 2007 by 63.5% and 27.7%, respectively.

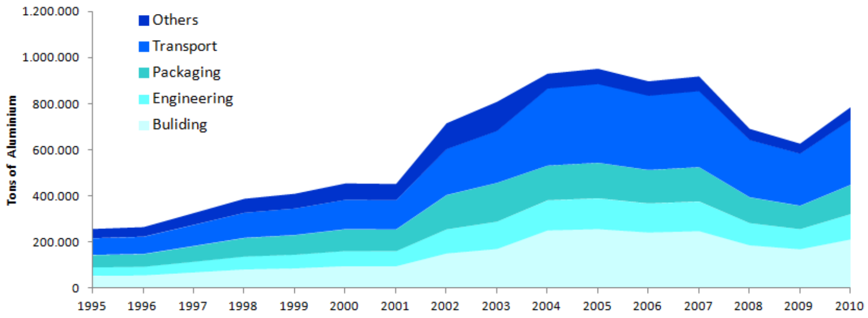

Figure 5: Production of final products by end use market expressed in tons from 1995 to 2010 in Spain

3.1.2. Scrap generation and consumption

After collection, new and old scrap is converted into secondary aluminium through refining and remelting. Figure 6 presents data on new and old scrap generation and consumption from 1995 to 2010; both new and old scrap generation and consumption have tripled since 1995. The increase in new scrap generation could correspond to the increase of semifinished and final products, as losses incurred during their production are classified as new scrap and reintroduced into the production chain. The increase in old scrap generation could correspond to improvements in waste collection, as well as the development of the Packaging Waste Directive (EU, 1994) and the End of Life Vehicle Directive (EU, 2000).

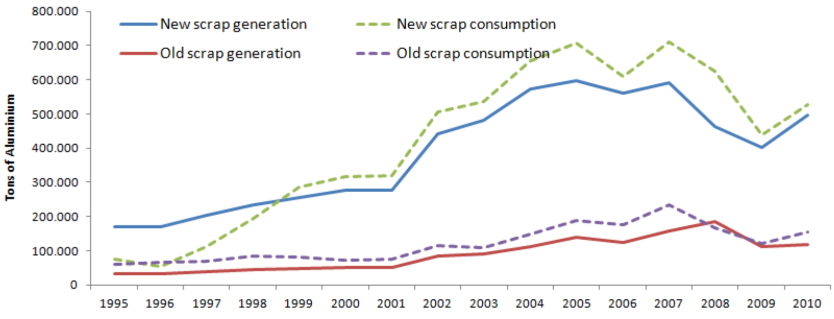

Figure 6: Old and new scrap collection and consumption expressed in tons of aluminium from 1995 to 2010 for Spain

Table 1 presents the packaging consumption and the waste packaging collection from 1999 to 2010, as well as the selective collection rate defined as the relation between waste packaging collected versus packaging consumed (Ecoembes, 2013, Arpal, 2013), which has increased considerably over the years. Nevertheless, packaging consumption decreased more or less constantly from 2002 to 2010. The aluminium content in domestic packaging has decreased gradually from 1965 to the present, which could justify the decrease in the weight of packaging consumed (Arpal, 2012). Conversely, the weight of packaging waste collected has increased regardless of individual weight, revealing the benefits of better selective collections and selection processes in waste treatment plants and improved waste recovery in incineration plants. The authors have found no statistics regarding the aluminium recovered from End of Life Vehicles (ELVs) in Spain, but data on total ELVs can be found from 2005 to 2010 showing that 82.5% recycling was achieved in 2010 (Eurostat, 2012).

Table 1: Packaging consumed, waste packaging collected and selective collection rate in tons of aluminium and percentage, respectively, from 1999 to 2010

	Packaging consumed (tons Al)	Waste packaging collected (tons Al)	Selective collection rate (%)
1999	45,961	1,542	3.36
2000	49,113	5,240	10.67
2001	57,907	7,668	13.24
2002	64,694	11,062	17.10
2003	45,656	11,710	25.65
2004	47,153	10,427	22.11
2005	50,187	10,231	20.39
2006	49,986	12,216	24.44
2007	52,416	14,145	26.99
2008	41,066	13,393	32.61
2009	40,584	13,412	33.05
2010	41,971	14,819	35.51

3.1.3. Trade of aluminium products

To observe the trade of aluminium products in detail, the bauxite trade was excluded in Figure 7. Figure 7 represents the commercial balance, defined as the difference between imports and exports of aluminium products; thus, lines above the horizontal axis indicate that there were higher imports than exports. Between 1995 and 2010, Spain experienced an excess of alumina production, which was exported, mainly to The Netherlands. During the same period, however, the positive balance of primary aluminium indicates that Spain experienced a deficit of primary aluminium and thus imported aluminium, mainly from Russia and Africa (datacomex, 2013).

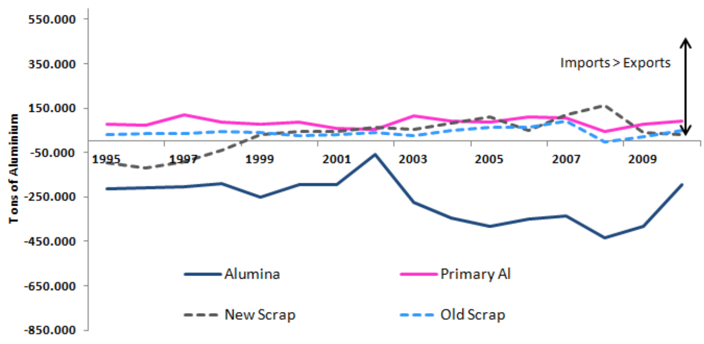

Figure 7: Commercial balances of aluminium in primary forms, new scrap and old scrap expressed in tons from 1995 to 2010 for Spain

In the case of secondary aluminium, divided into new and old scrap, we note that the new scrap commercial balance is negative during 1995-1999 because the excess of new scrap was exported. Since 1999, this trend was reversed, due most likely to increased secondary aluminium demand, and since 2008, there was a constant increase in new scrap imports (mainly from Germany) (datacomex, 2013). Old scrap consumption was higher than the supply for most of the study period, so Spain imported old scrap over this period; in the last year, the commercial balance approached zero, indicating that similar quantities of import and exports were traded. The most important change within the old scrap material trade is that while in 1995, old scrap was primarily exported to Europe (88%), the export flow has been shifting constantly to Asiatic countries (41% in 2010) (datacomex, 2013).

3.1.4. Stock of aluminium

Because the lifetime of many metal products can be between less than one year and more than 50 years, there has been an accumulation of metal in use since the start of the industry (JRC, 2010). There are no data available for Spain before 1995; therefore, our stock calculations are underestimated, considering that the aluminium industry existed for many years before the study period. However, in 2010, we calculated an accumulated stock since 1995 of 9,412,570 tons of aluminium, which represents approximately 11 years of supply of secondary aluminium at current consumption rates. Therefore, in subsequent years, this in-use stock will be an important source of old scrap to use in domestic production or to export abroad.

3.1.5. MFA for Spain in 2010

Figure 8 presents the flows, processes, stocks and losses included in each life cycle phase of aluminium. Figure 8 starts in 2010 because this year represents the most current situation. The arrows to and from the upper green rectangle represent movements to and from the international markets, and the arrows to the lower yellow rectangle represent movement to the environment.

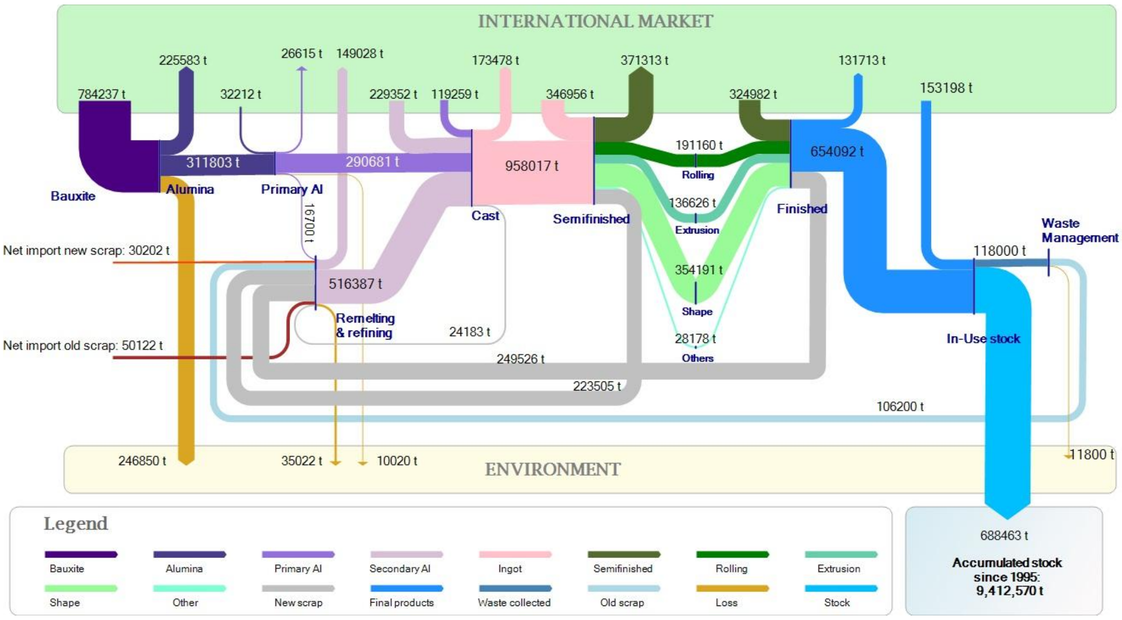

Figure 8: Aluminium value chain for Spain in 2010

3.2. Greenhouse Gas Emissions (GHG) of old aluminium recycling

Table 2 presents the GHG emissions for the waste management stage and recycling stage with same export percentages of old scrap as in 2010 (12.5% in China and 12.5% in Europe). Around 69% of the emissions due to waste management and recycling took place in Spain, while the rest were emitted abroad. Though the same data inventory for recycling was used for both Asia and Europe (i.e., the electricity needed for recycling), the results for the two countries are different due to the marginal electricity mixes considered for both regions; Asia has more contributions from coal primary energy. More information on the inventory and marginal electricity mixes can found in the Appendix B in Table B.1 and B.3.

Table 2: GHG emissions in kg CO_2 eq. by ton of collected old scrap aluminium in Spain when 75% of old scrap is recycled in Spain, 12.5% in China and 12.5% in Europe

	kg CO_2 eq. t^{-1}
Waste Management-Spain	**105**
Collection & sorting	94
National transport	11
Recycling	**980**
International transport	113
Recycling in Spain	629
Recycling in Europe	111
Recycling in Asia	127
TOTAL (kg CO_2 eq. t^{-1})	**1,085**

Table 3 presents the GHG quantifications for the scenarios A-global and B-local. We observe that the values obtained are very different because of the smelting and casting process (highlighted in grey). The smelting process is a high electricity consumer, and principal differences in the GHG results are due to the marginal electricity mix sources.

The marginal electricity mix of scenario A-global has higher contributions of coal than that of scenario B-local (see Table B.1 to B.3 in Appendix B). In fact, the emissions in scenario A-global are almost double those found for scenario B-local.

Table 3: GHG emissions avoided in kg CO_2 eq. by ton of collected old scrap aluminium in Spain for scenario A-global and B-local when 75% of old scrap is recycled in Spain, 12.5% in China and the remaining 12.5% in Europe

	Scenario A (global) kg CO_2 eq. t^{-1}	**Scenario B (local) kg CO_2 eq. t^{-1}**
Waste Management & recycling (*see Table 2*)	**1,085**	**1,085**
Primary aluminium	**-18,213**	**-9,012**
Smelting process & casting	-15,891	-6,915
Alumina	-1,640	-1,548
Anode	-334	-379
Bauxite	-30	-30
International transport	-318	-139
GHG quantifications for old scrap recycling	**-17,128**	**-7,927**

In both scenarios, similar GHG emissions are obtained for the alumina, anode and bauxite stages. We have observed that the emissions due to transport of old scrap to Asia and Europe contributes approximately 10% of the total emissions (see Table 2), similar to the entire emissions generated in Spain due to collection and sorting. If these emissions are compared to the whole GHG emissions from the market, including the avoided primary production, their contribution decreases up to 2%. Although the total contribution from the export of old aluminium scrap is small, we projected that in the future, export flows will most likely increase. Therefore, in Figure 9, we have evaluated the influence of the export flow on the GHG emitted by assessing the GHG emissions when the export flow varies between 0% and 100% and when 50% is recycled intra-EU and 50% extra-EU (China). The variations obtained in scenario A-global are less than 6%, while in scenario B, the variation is higher than 89%. This is due to the marginal process considered in both scenarios. In Scenario A-global, both Spanish recycling and international recycling avoid the global marginal primary production, and therefore, greater export flows increase the international transport stage, what has very little weight comparing to emissions due to the smelting process. However, in scenario B, when recycling occurs in Spain, Spanish primary production is the avoided process, but when recycling occurs outside of Spain, the global marginal production is avoided. Thus, increasing the export flows prevents more emissions because the global marginal production is decreased.

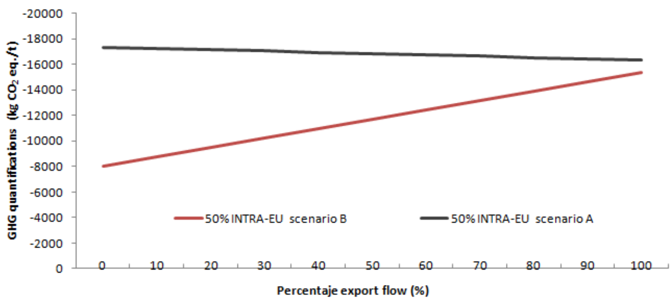

Figure 9: GHG quantification variations (in CO_2 eq. per ton of old scrap collected in Spain) for an export flow of 0% and 100%

4. DISCUSSION

4.1. Supply and demand of aluminium flows

Looking at the past trend of aluminium flows, we have observed that in the last few decades, Spain has been an exporter of alumina. It has simultaneously experienced a lack of primary aluminium, which had to be imported (from 18% in 1995 to 28% in 2010, relative to primary aluminium consumption). Additionally, there have been changes in the export flows of old scrap from Europe to Asia. Similar trends were detected and projected for Europe, including an increase in primary aluminium imports and old scrap exports over the period 2030-2050 (EAA, 2012a). In fact, the European Aluminium Association (EAA) has noted that Europe's imports of primary aluminium are due to European primary producers' lack of economic competitiveness, mainly due to the price of electricity, which is the critical factor in the production of aluminium. Large uncertainties are besetting the industry, and if the current situation is not reversed, Europe and Spain will become increasingly dependent on imported primary aluminium. This may, in the long run, also negatively affect the fabrication of semifinished products (EAA, 2012a), an industry that contributes heavily to aluminium recycling. In this sense, the MFA has revealed that in recent years, more old scrap was available in Spain due to improvements in recovery and collection, and the amount available is expected to increase in the coming years due to in-use stock products reaching their end of life, especially in the transport sector.

At the global scale, approximately 75% of the aluminium produced is still in stock (approximately 700 Mt) (Rombach, 2013), so cities have likely become huge reserves of anthropogenic aluminium that will be an exploitable source in the future (Ciacci et al., 2013). However, an increase in the efficiency of old scrap collection has a significantly smaller impact on the relative availability of secondary raw materials than the growth in future demands for aluminium (Rombach, 2013). The demand for both primary and secondary aluminium is projected to increase in the future, especially demand for secondary aluminium due to the increasing application of aluminium in light vehicles. It has been predicted that the aluminium industry will be displaced to developing countries (Menzie et al., 2010; JRC, 2007). Thus, if the primary aluminium industry is affected and consequently the semifinished industry, but at the same time more old scrap is available due to more stock at the end of its life, the export of old scrap will increase in the future to countries with high demand, which are almost all derived from developing China.

4.2. Benefits of recycling in terms of CO_2 eq.

Regarding the GHG consequences of the projected situation, we note the importance of considering the trade, as the avoided primary aluminium production will determine the benefits of aluminium recycling, and depending on the marginal source considered, important differences were obtained. Environmental reports on aluminium smelters that consider this perspective are very limited (Damgaard, 2009). However, a few studies (McMillan, 2012; Schmidt and Thrane, 2009; Koch and Harnisch, 2002) have explored the regional variances for primary aluminium production where the main influence was the energy source and results varied from 5.9 kg CO_2 eq. kg^{-1} of primary aluminium for a new smelter in Greenland with a hydropower energy supplier (Schmidt and Thrane, 2009) to 22.5 kg CO_2 eq. kg^{-1} of primary aluminium in Asia as a result of the region's intensive use of coal fired electricity generation (McMillan, 2012). Those results agree well with our result that 18 kg of CO_2 eq. kg^{-1} will be emitted for global marginal primary aluminium production traded in a global market, and 11 kg of CO_2 eq. kg^{-1} will result from the Spanish primary aluminium production.

As far as we know, there is no study that quantifies GHG emissions due to old scrap recycling by considering different marginal sources of primary aluminium or taking into account the dynamics of the market for the old scrap. In most cases, primary aluminium production is considered to be avoided by recycling, but previous studies have been limited to national boundaries and nationally or regionally averaged data. The values reported varied between -11,100 kg CO_2 eq. per ton of old scrap (Prognos, 2008) to -3,540 kg CO_2 eq. per ton of old scrap (BIR, 2008); and from -14,958 kg CO_2 eq. per ton (US EPA, 2006) to -9,074 kg CO_2 eq. per ton (AEA, 2001) of aluminium cans collected. If this study was limited to the Spanish boundaries and averaged inventory data, the GHG emissions avoided would be estimated to be around -8,971 kg CO_2 eq. t^{-1} per ton of old scrap collected.

However, as this study reflects, reality is much more complex, and to consider that neither the primary and secondary aluminium industries nor the resulting GHG estimates are affected by the market dynamics is incorrect and incomplete. Therefore, it is necessary that the method for accounting for the GHG impact of recycling reflect the market mechanisms, especially if the GHG estimates are to inform waste management policies and strategies. The GHG estimates obtained in this study vary between -17,000 kg of CO_2 eq. t^{-1} of old scrap collected to -10,000 of CO_2 eq. t^{-1} of old scrap collected, depending on whether the situation is more global or local, respectively. This difference is significant enough to warrant further exploration. For example, assuming that Spain collects a constant amount of approximately 118,000 tons of old scrap annually, the two scenarios produce very different results and conclusions. In addition, the importance of including market dynamics is highlighted when export flows are taken into account. As demonstrated by Figure 9, if the amount of old scrap exported increases, the GHG estimate also increases due to the global marginal primary aluminium substitution (i.e., higher benefits of recycling are obtained).

Recycling should be promoted because it means less energy consumption and thus leads to significant savings in GHG emissions compared to primary production, which is confirmed by the results of this study. On the other hand, when the global trade is considered, higher GHG savings result because more polluting primary production is avoided as a consequence of recycling. In this sense, we have forecast an increase in the export flows what will provide greater GHG savings in a global market. However, it should be noted that the efforts made in recent years to increase collection rates and improve collection systems are not being rewarded because the benefits of recycling are occurring in other countries. Moreover, the results suggest that if the market rules remain the same, efforts to reduce the impacts associated with primary production will be lost as production moves to other countries with higher environmental impacts. These results were obtained by analyzing the impacts of recycling old scrap, but as the MFA reflects, this process's life cycle is interrelated with other processes (i.e., primary aluminium production or semifinished production), so evaluating the consequences in terms of the GHG emissions due to other life processes (for example, the effects of primary aluminium imports) could lead to different results or to an increase in the estimate of global GHG emissions. Therefore, although this analysis predicts greater GHG savings due to the globalization of the old scrap market, export flows are against the objectives of the CE, and from a material point of view, it is essential to reverse the increasing trend in the export of aluminium scrap because it allows importers in other regions to capture a key resource.

5. CONCLUSION

The integration of the MFA and CLCA is an effective method for evaluating the aluminium flows and estimating GHG emissions within a market context. For the case of Spain but also for Europe, where similar trends were reported and projected (Menzie et al., 2010; JRC, 2007), this methodology has allowed us to observe the trends in past years in the aluminium industry and forecast that if the current trend is not reversed, the primary aluminium industry will be displaced to developing countries and old scrap exports will therefore increase. In fact, developed countries in the 21st century are becoming the major suppliers that provide raw materials to developing countries. In this regard, the GHG results show that the increase in old scrap exports avoids more GHG emissions than if the old scrap is recycled locally, providing up to 89% more in GHG savings. However, the displacement of primary aluminium production implies a loss of local industry, and the export of old scrap should be considered as the loss of a key resource that, in the long term, will also affect the semifinished products industry in a “cascade effect”. Moreover, in the medium and long term, both Spain and Europe as a whole will have to deal with significant quantities of old scrap from in-use stock, and if there is no consolidated industry, this valuable resource will be lost. To achieve a CE with a systemic change in the use and recovery of resources in the economy, different strategies should be proposed for the waste management system and the recycling and primary industries in order to adapt the industry to the future material and quality flows and to reduce import dependence and the loss of material through the export of old scrap.

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