A report by:

OAKDENE HOLLINS
RESEARCH & CONSULTING

for the:

International Magnesium Association

Magnesium Recycling in the EU

Material flow analysis of magnesium (metal) in the EU and a derivation of the recycling rate

Value-driven consulting *Science-led research*

Magnesium Recycling in the EU

Material flow analysis of magnesium (metal) in the EU and a derivation of the recycling rate

Value-driven consulting

Science-led research

Written by: Nia Bell, Rachel Waugh and David Parker

Final check by: Katie Baker

Approved by: Peter Lee

Date: 07/06/2017

Contact: david.parker@oakdenehollins.com

Reference: IMA-09 454.docx

Contents

List of tables

List of figures

Glossary

Al	Aluminium
ATF	Authorised Treatment Facility
BAT	Best Available Technique
CRM	Critical Raw Material
ELV	End of Life Vehicle
EoL	End of Life
EoL-RIR	End of Life - Recycling Input Rate
EoL-RR	End of Life - Recycling Rate
HS	Harmonised System
LCA	Life Cycle Assessment
Mg	Magnesium (metal)
MSA	Material System Analysis

Units

Conventional SI units and prefixes used throughout: {k, kilo, 1,000} {M, mega, 1,000,000} {T, metric tonne, 1,000 kg}

Contents amendment record

This report has been amended and issued as follows:

Version	Date	Description	Author	Editor
1	25/05/2017	First draft submitted to IMA	NB, RW	DP
2	07/06/2017	Final version	NB, RW	DP

Acknowledgements

We are extremely grateful for the excellent input we received from industrial and academic stakeholders as part of our research.

ACEA
Advanced Alloy Services
Almamet
ASM Recycling
Avon Metals
Birmingham City University, UK
BMRA (British Metals Recycling Association)
Brunel University, UK
CAEF (European Foundry Association)
DLR (German Aerospace Centre)
EAA (European Aluminium Association)
FEDEREC (French Federation of the Recycling Industry)
Husqvarna
IMA (International Magnesium Association)
Innoval
Jaguar Land Rover
Magnesium Elektron
Magontec
Meridian Lightweight Technologies
MPIUK (Materials Processing Institute UK)
MVDA (Motor Vehicle Dismantlers Association)
non ferrum
Real Alloy Germany GmbH
Roskill
SKW Metallurgie
Stihl
Tata Steel
W. Pilling Kesselfabrik GmbH & Co.

1 Executive summary

This report, prepared on behalf of the International Magnesium Association (IMA), presents the findings of a comprehensive material flow analysis of magnesium (metal) in the EU for 2012. This study's findings supersede those presented for magnesium (metal) in the 2015 Material System Analysis (MSA) study produced for DG-GROW.[1] We suggest that this magnesium (metal) material flow analysis is superior to that in the MSA study for three key reasons:

- There is more official data now available on 2012 flows than when the MSA study was conducted.
- Input from industry stakeholders was sought for this study, and received.
- Valuable input and sense checks have been provided by the IMA steering board at each stage of the research.

Whilst alternative data sources were sought and estimates refined, the overall approach to the material flow analysis employed here was the same as in the MSA study in terms of flows, notations and definitions. The results of both studies can therefore be compared like-for-like. However, given that this study focusses on one material only, while the MSA study covered the 21 materials (or families of materials) identified as critical to the EU, this study is able to go into much more detail on individual streams.

As with the MSA study, one key output of this work is a high-level Sankey diagram (see Figure 1) of the inputs and end-fates of magnesium (metal) - hereafter referred to as Mg - in the EU. Even a brief inspection of the diagrams in Figure 1 highlight some of the main differences in the findings of this study compared to those reported in the MSA study:

- This study finds the figure for Mg imports into the EU is 18% higher than reported in the MSA study.[2]
- This study finds exports are over double those identified in the MSA study.
- Landfill in the EU is only 30% of that identified in the MSA study.
- The MSA study includes only old scrap functional recycling, while this study also quantified functional recycling of new scrap.[3]
- Non-functional recycling of Mg is an order of magnitude higher than in the MSA study,
- Instead of 9 kT of de-accumulation as in the MSA study, this study found there were 34 kT of in-use Mg accumulation.[4]

Rather than justifying here each of these considerable differences between the material flow analysis derived in this study and that in the MSA study, readers with an interest in the data sources, calculations and estimates used are directed to the Results chapter of this report where each flow is described in detail. Though constraints posed by data availability did

---

[1] Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials, DG GROW, 2015 https://ec.europa.eu/jrc/en/scientific-tool/msa

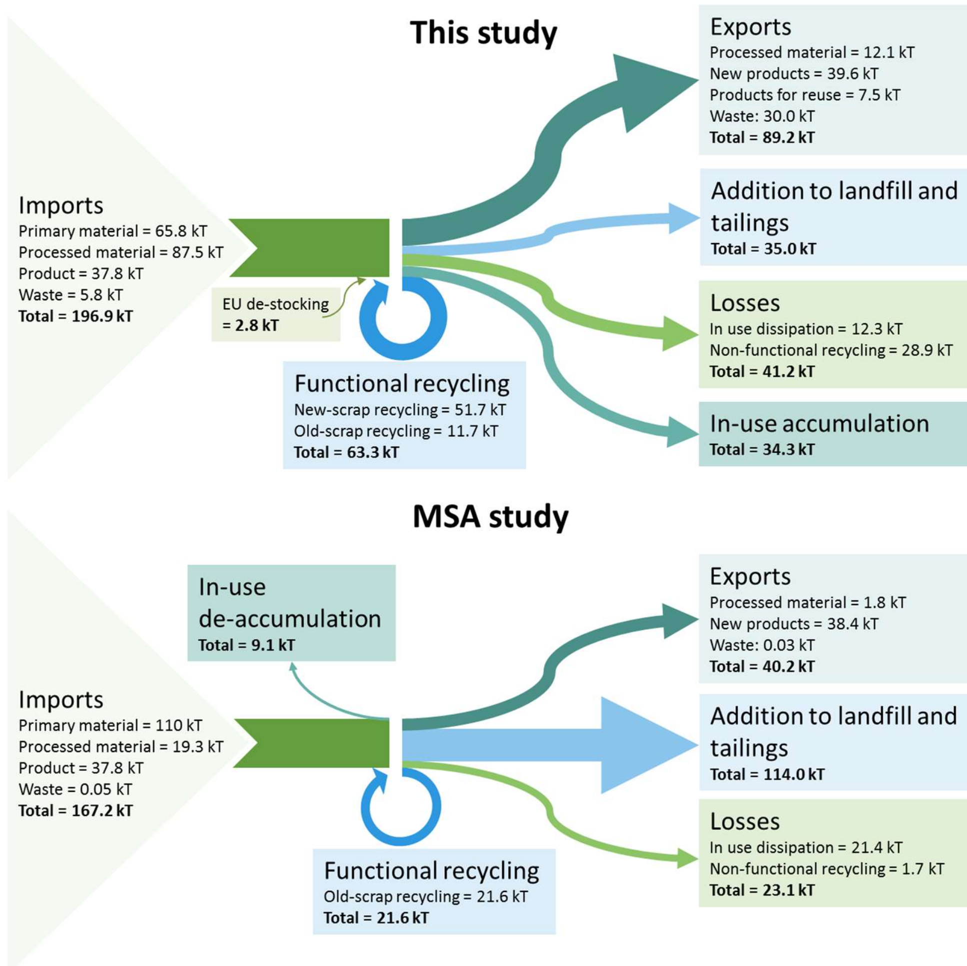
[2] The difference arises from the fact that the MSA study only used customs data to quantify imports and exports and they did not always use the same trade codes and assumptions as in this study. This study also used World Aluminium's 'Global Aluminium Flow' to assign values to some of the import and export flows.

[3] 'Old scrap refers to EoL, post-consumer scrap and 'new' scrap to the scrap generated in manufacturing processes which generally has a known composition and origin.

[4] In-use accumulation/de-accumulation refers to the change, either positive or negative respectively, in Mg stockpiled in products being used in the EU in a given year.

mean that there were cases where estimates, proxy measures and assumptions had to be employed to quantify flows, we are nevertheless confident that the material flow analysis derived here presents a more accurate picture of Mg use within the EU, than that in the MSA study.

Figure 1: High level Sankey diagram for magnesium (metal) produced in this study (Top) compared to that output from the MSA study (Bottom)



The bottom-up approach applied to developing the material flow analysis, i.e. quantifying each flow per application of Mg individually and then summing them together to get the values presented in Figure 1, meant that we could also determine how much Mg is used in which applications the EU.

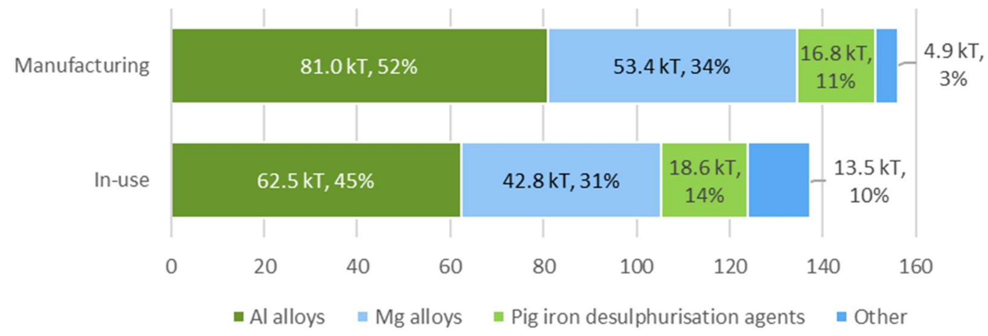
Widely cited figures originating in a Roskill report allocate 40% of Mg in the EU to aluminium (Al) alloys, 39% to die-casting, 12% to pig iron desulphurisation and 9% to 'other' applications.[5] In deriving a similar application split from the material flow analysis we found

---

[5] Application split used by IMA, from Roskill's report on magnesium metal: global industry markets and outlook (https://roskill.com/product/magnesium-metal-global-industry-markets-outlook/). Note, that there is slight confusion as to whether this is the use of Mg in the production of these products or this is the amount of Mg consumed in these products in the EU. Depending on the level of imports and exports of finished products the difference can be significant.

that it was important to define which stage of the flow was being considered. Understandably, given the considerable imports and exports of finished Mg-containing products from the EU, the application split of the Mg used by the EU's manufacturing sector is different to that used in the EU by consumers (see Figure 2). Though this study allocated more Mg use to Al alloy applications than Mg alloy applications, the application split derived for Mg use in the EU is not that dissimilar to the Roskill figures.

Figure 2: Consumption of Mg in the EU in 2012 in manufacturing vs in the in-use stage



Note: 'Other' applications of Mg include the Mg powder applications (Grignard reagents, pyrotechnics and refractory materials) as well as the Mg used in nodular cast iron.

The End of Life - Recycling Input Rate (EoL-RIR) for Mg in the EU was also derived from the material flow analysis data. At 7% the EoL-RIR of Mg is low, lower than that of Al at 12% (global, not EU specific value). This was not unexpected given the dispersive nature of some of Mg's applications, and the collection and recycling inefficiencies discussed in detail in the relevant flows in the Results chapter of this report. The main improvements in collection and recycling efficiencies that could increase the recycling rate of Mg are:

- Greater dismantling of Al and Mg alloy components from ELVs.
- Even higher collection rate of EoL aluminium beverage cans.[6]
- Technological advances in the automated sorting of Al alloy fractions from shredding.
- Diverting more high Mg-containing Al alloys to remelters, who generally try to retain the Mg in their input materials, rather than by refiners, who do not.
- Diverting more segregated EoL Mg alloys to specialist Mg recyclers.
- Better slag utilisation by the Al and steel industries (non-functional recycling only).

This list highlights the fact that the recycling rate of Mg is very dependent on the activities of the aluminium and, to a lesser extent, the steel industries. Identifying best practice for Mg retention in Al alloy recycling requires further investigation in order to identify more targeted opportunities for its improvement. It would also be interesting to calculate what the maximum realistic recycling rate of Mg would be in the EU if current, and forecast, best practice methods for Mg retention were fully implemented.

In spite of this reliance on other industries we predict that Mg recycling in the EU is increasing. Even since 2012, the baseline year for this study, the collection rate of EoL Al

[6] Voluntary target of 80% by 2020 adopted by industry, up from approximately 70% in 2012. (http://european-aluminium.eu/media/1038/2016-01-21-european-aluminium-press-release-alubevcanrecycling_.pdf)

beverage cans has increased and there are policies being enacted, such as research into new technologies,[7] to improve the competitiveness of ELV processors. The policies concerning ELVs are driven by the ambitious recycling targets for ELVs in the EU. Meeting these targets is reliant on a strong ELV processing sector. However, the sector is facing an overall decline in the steel content of vehicles, which is a problem as the plastics and composites they are partly being replaced with are typically of a lower value and more difficult to recycle.[8] The material and value extraction from the Al and Mg alloys in ELVs will help offset the decrease in revenue from steel and contribute to the EU achieving its ELV recycling targets.

[7] For example, the EU funded projects REALCAR2 and REALITY and SHREDDERSORT

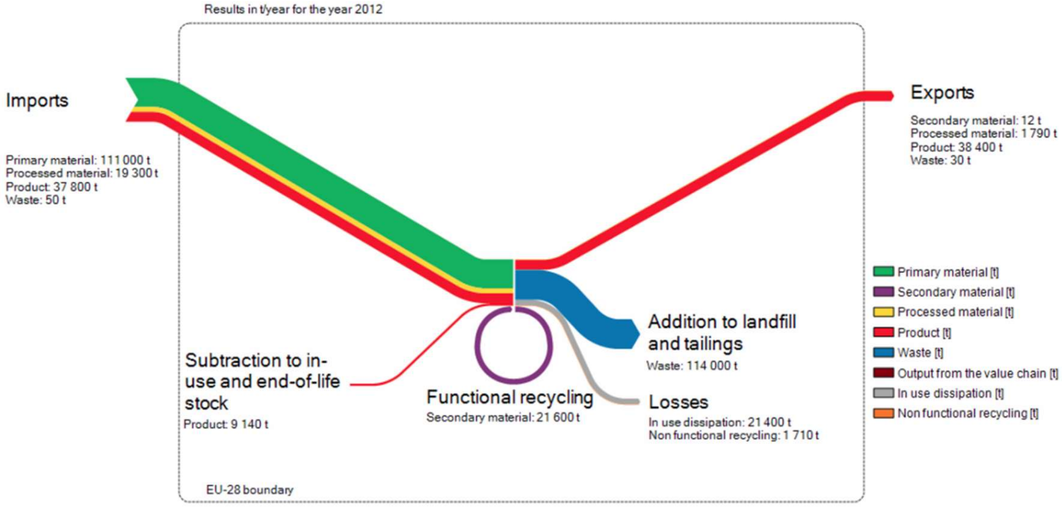
[8] Steel perspectives for the automotive industry, P. Blain (OICA) 2012 (https://www.oecd.org/industry/ind/50498824.pdf)

2 Introduction

In this report, we present a complete material flow analysis of magnesium (metal), hereafter referred to as Mg, in the EU in 2012. This report was commissioned by the International Magnesium Association (IMA) and carried out independently by Oakdene Hollins.

The main motivation for commissioning this study was the recent publication of a material flow analysis for Mg as part of the EC's Material System Analysis (MSA) of critical materials.[9] This analysis estimated that 114 kT, or 68%, of total Mg used in the EU was landfilled or added to tailings in 2012. Conversely, in a paper about Mg in the USA[10], only 21.5 kT of Mg landfilling was identified, or 19% of the USA's 2012 consumption. The large disparity between these figures, as well as the IMA's general understanding of their industry, convinced them that the landfill rate reported from Mg in this study was far too high.

Figure 3: Simplified Sankey diagram for Mg as reported in MSA of critical materials report



Source: Study on Data for a Raw Material System Analysis, DG GROW, 2015

As well as the controversial landfill rate for Mg reported in the MSA report, the subtraction of Mg from in-use (and end of life, EoL) stock and the low level of functional recycling were also questioned by members of the Mg industry. This study was thus commissioned to rectify the misleading information in the MSA study.

The importance of having accurate and reliable information on the recycling rate of materials cannot be underestimated. The recycling rate is a key input used in life cycle analysis (LCA) calculations and can influence public and company policies on using and promoting the use of materials. Recycling is also a key mitigating strategy for minimising supply risks associated with sourcing primary materials. This is particularly true for Mg, which has been categorised as a critical raw material (CRM) by the EC[11], because of its lack of domestic primary supply as

---

[9] Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials, DG GROW, 2015 https://ec.europa.eu/jrc/en/scientific-tool/msa

[10] Market dynamics, recycling and recovery of magnesium from aluminium alloy scrap: A.J. Gesing and S.K. Das, Applications of Process Engineering Principles in Materials Processing, Energy and Environmental Technologies: A Symposium in Honor of Professor Ramana G. Reddy, Taylor Springer, Feb 2017

[11] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

well as its importance to certain European manufacturing sectors. Finally, it is necessary to know the baseline recycling rate in order to measure improvements in the recycling rate and monitor the success of measures taken towards achieving a more 'circular' economy.

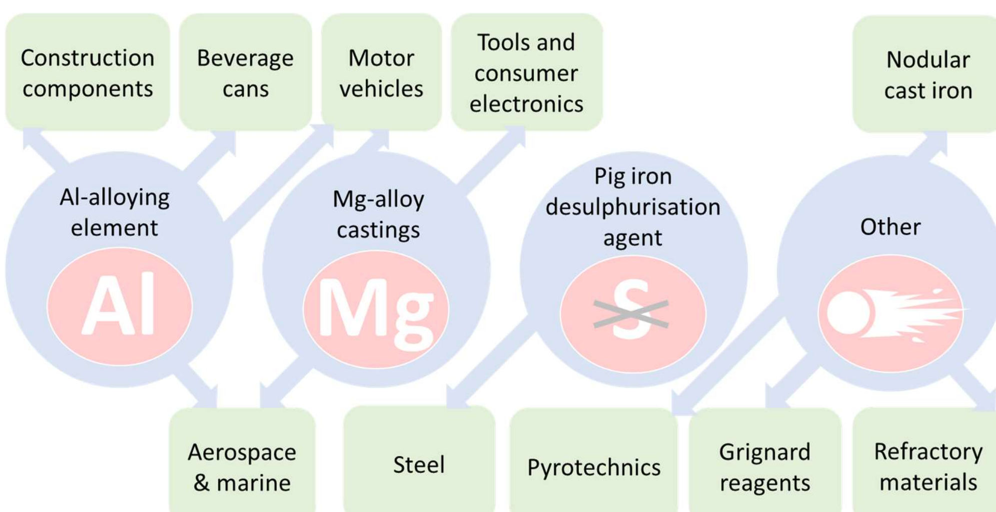
Carrying out a complete analysis of all the material flows related to Mg not only allowed us to derive a recycling rate but also enabled us to identify where there may be opportunities to reduce the losses of Mg from the system.

A materials flow analysis also demonstrates the importance of Mg to the EU economy and everyday products such as aluminium (Al) beverage cans, motor and aerospace vehicles, consumer electronics and steel. The main applications of Mg are shown in Figure 4 below. A major application for Mg is in Mg alloys. These contain approximately 93% Mg and are cast into lightweight components for cars and other vehicles, as well as being used in high-end power tools and consumer electronics. Of similar importance in terms of Mg consumption in the EU is the use of Mg as an alloying element with Al. The addition of small amounts of Mg, typically <5%, to Al increases its strength so it can be used in structural applications such as in construction and pressurised containers (e.g. beverage cans).

Mg is also used in producing steel from iron ore. Iron sulphide is an impurity in iron which, if not removed, leads to unacceptable brittleness in the steel. Mg has a high affinity to sulphur meaning that less material and time is required for it to remove the unwanted sulphur, compared to other desulphurisation agents.

There are other, varied applications of Mg not limited to those shown in Figure 4. Some of these applications are of either powdered or granulated Mg, e.g. Grignard reagents, pyrotechnics, and refractory materials. Grignard reagents are halogenated Mg compounds used to create certain carbon-carbon bonds by the chemical industry. The bright light of burning Mg makes it a key constituent in pyrotechnics including flares and fireworks. Mg, in oxide form, is also used as a refractory material in the steel and chemical industries. The final application considered here is the use of Mg to change the shape of the carbon inclusions in cast iron from flakes, which cause brittleness, to spherical nodules. This Mg-treated cast iron is known as nodular cast iron or ductile cast iron.

Figure 4: Main applications of Mg in the EU



OAKDENE HOLLINS
RESEARCH & CONSULTING

3 Methodology

3.1 Goal and scope definition

The goal of this research was to carry out a thorough material flow analysis for Mg in the EU in 2012 and to derive a recycling rate. The material flow analysis was to be carried out in such a way that the underlying data and assumptions would be completely transparent and justifiable to an interested reviewer. Furthermore, a high-level summary of the material flow analysis should be presented in a way that clearly communicates the key learnings from the study to the intended audience, i.e. industry stakeholders, policy makers and researchers.

The scope of the study has been set to mirror that used in the recent Material System Analysis (MSA) study produced by the EC[12], i.e. using a baseline year of 2012 and the EU27 as the geographical scope. This was done to facilitate comparisons between the material flow analysis for magnesium produced here to those of magnesium and the 20 other materials covered in the MSA study.

3.2 Approach

The overall approach we took for this study consisted of:

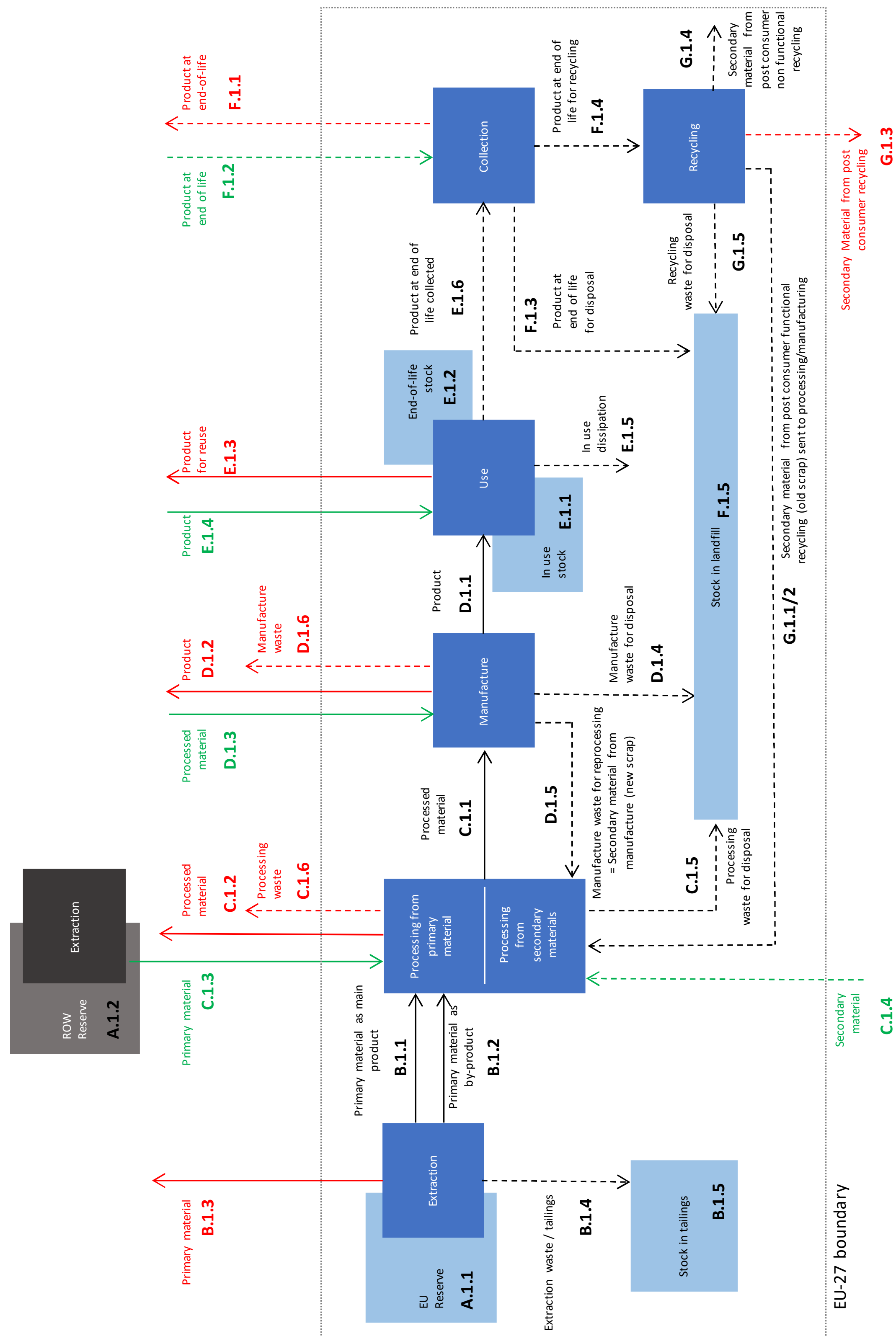
- identifying data sources, including literature and industry experts, and exploiting them
- carrying out the material flow analysis, using spreadsheets to check the mass balance of each sub-flow at each stage
- creating flow diagrams, to help visualise the flows of Mg in the EU
- creating Sankey diagrams, as another way to visualise the flows of Mg in the EU
- compiling all findings into a report set out as transparently as possible.

3.2.1 Data gathering

By far the most important stage of this study was that related to identifying and mining data sources that could be used to quantify the flows in the material flow analysis. Most the hard-numeric data we identified, largely related to trade and waste reporting, is included in Annex A to Annex C of this report. It was also vital to identify the data gaps, for which we were obliged to use proxy measures, estimates and assumptions to quantify the flows in the material flow analysis.

[12] Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials, DG GROW, 2015 https://ec.europa.eu/jrc/en/scientific-tool/msa

Figure 5: Depiction of generic material flows labelled according to the MSA methodology



Source: The spreadsheets supporting the magnesium data workup for the MSA report, shared by the IMA

Stakeholder engagement was the focus of the data-gathering part of this research. We approached approximately 60 individuals via email and telephone with questions tailored to their area of expertise related to Mg. The bulk of this research was carried out between March and April 2017. The IMA steering committee contributed to this stage of the study by suggesting contacts and even, in some cases, providing us with introductions. However, we also exploited our own contact network, approached companies found through web-searches and followed leads provided by the experts we had already spoken to.

The interest, and thus response to our approaches and questioning, was highest in the industries directly related to Mg, i.e. Mg casting, alloy production and recycling. We found it more difficult to engage sources in the Al industry and in the end of life vehicle (ELV) processing sector. We therefore had to rely more on literature sources and assumptions in these flows.

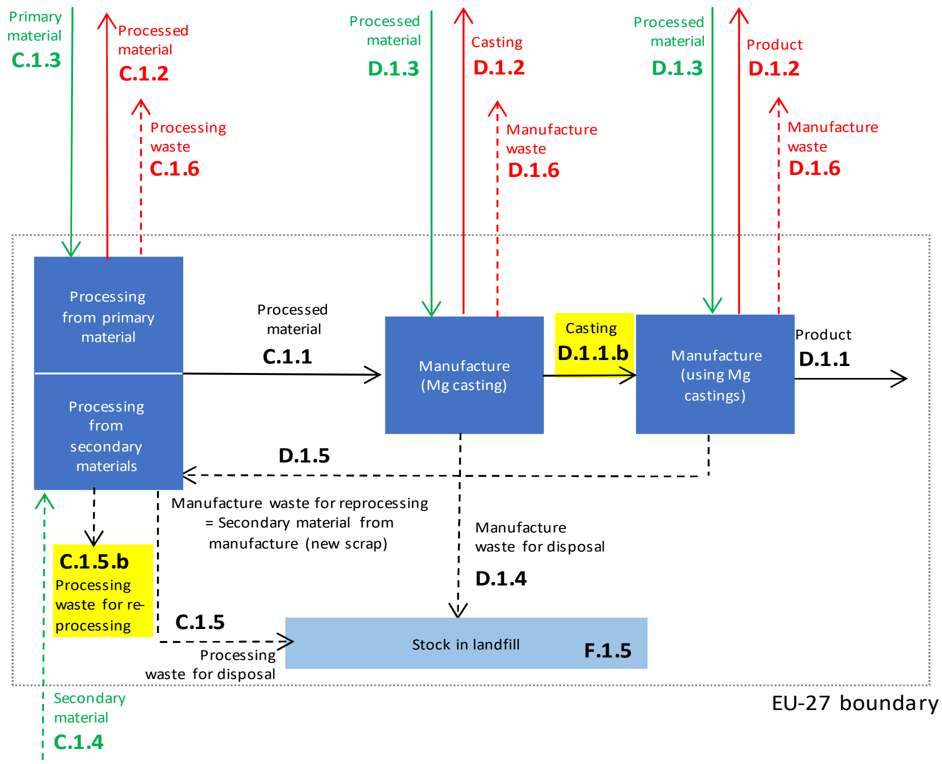
3.2.2 The material flow analysis

As well as basing the study's scope on that of the MSA study, the general approach to carrying out the material flow analysis was kept consistent with that of the MSA. Again, this was for comparability between the results of both studies. The MSA approach consists of splitting the flow of a material through the economy into a series of discrete stages (extraction, processing, manufacturing, use, collection and recycling) and considering all the inputs and outputs of each stage in turn (see Figure 5). The amount of material going in and out of each stage should balance, as should the amount of material going in and out of the entire system. This should also be true of individual sub-flows, e.g. Mg's use in Al packaging, as well as the overall flow of Mg at a certain stage.

We found the generic MSA approach to Mg needed modest adjustment through creating a few flows additional to those labelled in Figure 5 (see Figure 6). One of these flows was associated with splitting the manufacturing step in the Mg-alloy sub-flow into casting production and finished article production (i.e. the use of the castings in cars, tools or other equipment). This required the addition of an internal flow we refer to as D.1.1.b and is defined as '*Mg in castings: cast components production sold in the EU*'. The second flow we added is one to capture non-functional recycling of wastes from the processing stage. Labelled as C.1.5.b and defined as '*Mg in magnesium alloy waste sent for reprocessing in EU'* this flow captures the treatment of slags from primary and secondary Al alloy production as well as slags from Mg alloy remelting and primary production.

The quantification of each material flow is reported to the nearest 100 T. This allowed us to capture some of the smallest Mg flows in the EU. It could be argued that reporting to the nearest 100 T suggests a level of certainty unsupported by the underlying data and assumptions. The presented data could, if preferred, be further rounded to the nearest kT.

Figure 6: Material flows used in this study



Source: Oakdene Hollins refinement of diagram from spreadsheet supporting the magnesium data workup for the MSA report; additional flows highlighted in yellow, alongside those used in the MSA study.

3.2.3 Visualising the results: flow and Sankey diagrams

There are pros and cons of both flow and Sankey diagrams, and we have included both. Some individuals will prefer one over the other, or study one rather than another depending on what they want to learn from it. In flow diagrams, all flows appear the same size, meaning that the largest flows do not obscure the smallest flows. This can be useful in checking mass balances and probing the smaller flows, but can distort the perception of which flows are more important. Sankey diagrams, as included in Annex D, address this distortion by scaling the flows depending on the Mg content they represent.

The flow diagrams were produced with Microsoft Visio, and eSankey was used to produce the Sankey diagrams.

3.2.4 Report structuring and writing

This report's structure is designed to clearly and concisely present the findings of the study as well as include all supporting information needed to probe and build on the results for subsequent studies. Each Mg sub-flow is detailed in turn in the Results chapter of this report. At the end of each section on each sub-flow is a list of the key-findings from that sub-flow. In the Conclusions chapter the report all the sub-flows covered in the Results chapter are brought together and Figures and discussion on the overall Mg flows presented.

For information on how individual flows were quantified, there are fully referenced tables of sources, calculations and estimates in each sub-flow section of the Results chapter. Annex A to Annex C also contain tables on trade, waste reporting and alloy composition, amongst others.

3.3 Definition of the End of Life - Recycling Input Rate

One metric that can be derived from the information contained in a material flow analysis is the End of Life - Recycling Input Rate (EoL-RIR) for Mg in the EU. The EoL-RIR is a useful measure of the proportion of old scrap Mg input into the EU's processing stage. For the purpose of this study we are defining the EoL-RIR as:

$$\mathrm{EoL-RIR} = \frac{Input\ of\ 2ary\ material\ from\ old\ scrap\ to\ the\ EU}{Input\ of\ 1ary\ material\ to\ the\ EU + Input\ of\ all\ 2ary\ material\ to\ the\ EU}$$

$$= \frac{G.1.2}{C.1.3 + D.1.3 + C.1.4 + G.1.2}$$

Note: only non-zero flows included in this definition of EoL-RIR, i.e. flows G.1.1, B.1.1 and B.1.2 excluded.[13]

The EoL-RIR is one measure of how reliant an economy is on primary material and is thus particularly relevant to determining a material's criticality, as the EC has been doing in its lists of critical raw materials to the EU.[14]

However, the EoL-RIR is not the only 'recycling rate' of interest to consider. For example, the End of Life - Recycling Rate (EoL-RR) is a measure of the efficiency of the collection and recycling stages of EoL Mg. Defined as:

$$EoL - \qquad \frac{G.1.2}{E.1.6 - F.1.1 + F.1.2}$$

the EoL-RR quantifies the fraction of metal contained in EoL products that is collected, pre-treated, and finally recycled back into the anthropogenic cycle.[15]

[13] Based on MSA methodology for deriving the EoL-RIR

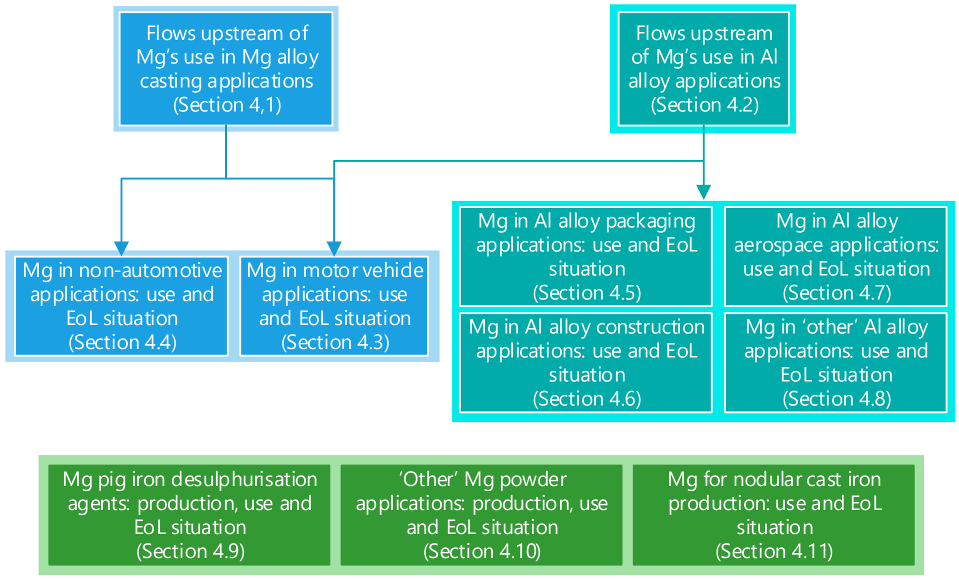
[14] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

[15] Tercero Espinoza, Luis Alberto; Soulier, Marcel (2017), Defining regional recycling indicators for metals: An extension of global recycling indicators to regional systems with open boundaries, Working Paper Sustainability and Innovation, No. S04/2017

4 Results: breakdown of each sub-flow

To present the Mg flows in the EU in a clear and structured manner, we have split the overall flow diagram into 11 separate sub-flows as illustrated in Figure 7.

Figure 7: Sub-flows of Mg described in this Chapter



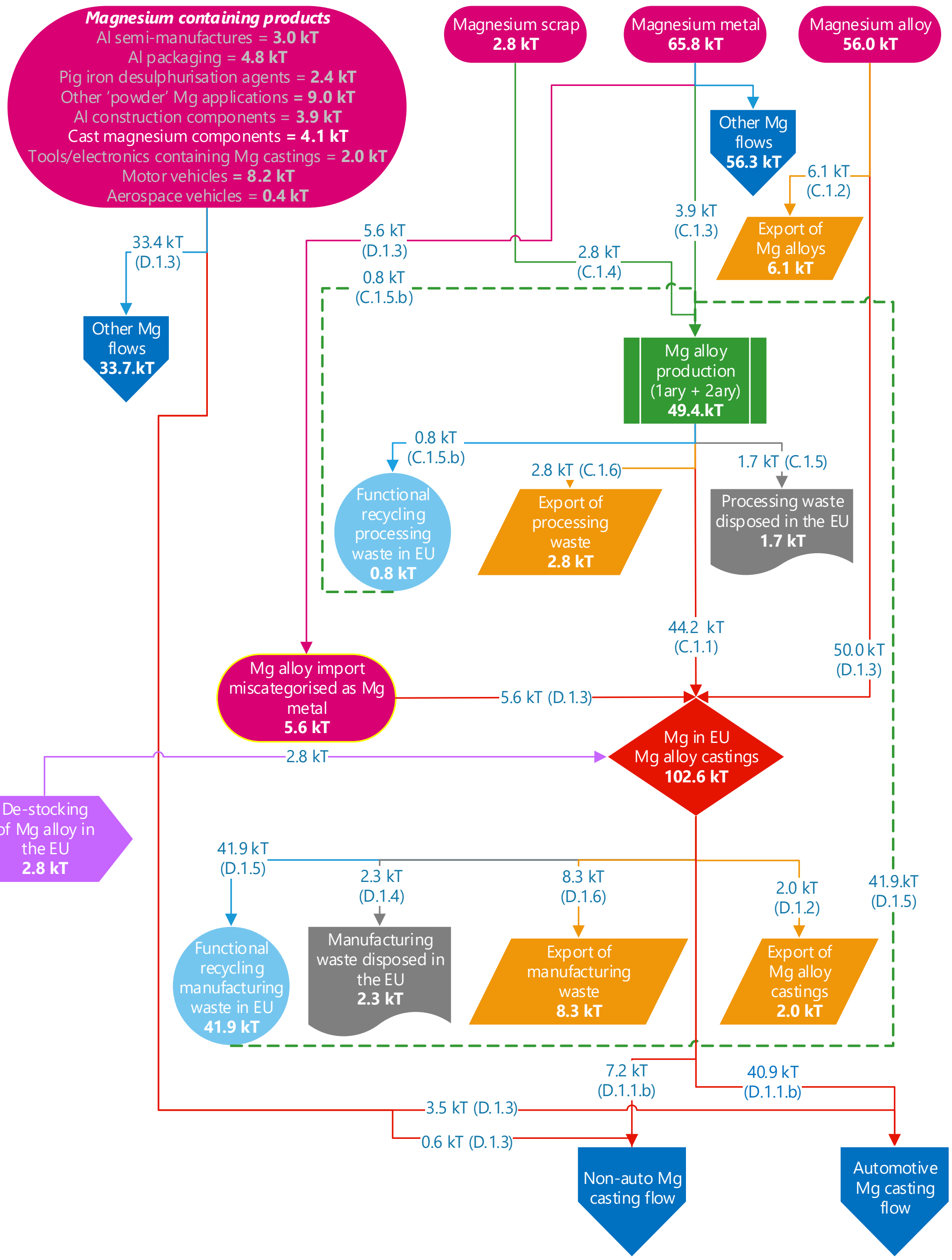
Each of these sub-flows will be described in a dedicated section below following a similar structure. They will contain a map of the sub-flow and a table outlining the sources, calculations and assumptions used to derive each material flow, and will be structured into three main sub-sections:

1. High-level description of the sub-flow.
2. Discussion of any discrepancies and uncertainties encountered.
3. Key findings from the sub-flow.

4.1 Flows upstream of Mg's use in Mg alloy castings

Figure 8 is a map of the flows upstream of Mg's use in Mg alloy castings. These flows are also depicted in the Sankey diagram in Figure 27. The flows are labelled with codes (C.1.3, D.1.2 etc.) used to refer to them in the text. The sources and calculations used to derive each flow are listed in Table 1 at the end of this sub-section.

Figure 8: Map of flows upstream of Mg's use in Mg alloy casting applications



4.1.1 High level description of the sub-flow

Mg alloy castings are primarily made in foundries specialising in working with Mg alloys only or with Mg and Al alloys. Depending on the type (sand or die) and size of their casting equipment, foundries further specialise in Mg alloy castings for different applications, e.g. aerospace, automotive or power tools.

Foundries typically source primary Mg alloys directly from producers, mainly in China (D.1.3). There is also a relatively small amount of primary Mg alloy production in the EU, circa 4 kT, mostly consisting of speciality and master alloys.[16] This primary Mg alloy production relies on the import of pure (>99.8%) Mg metal into the EU, again mainly from China (C.1.3). See Table 12 and Table 14 in Annex A for information on the geographical origin of the Mg alloy and metal imported into the EU.

To balance the amount of Mg castings produced in the EU with the use of Mg castings in automotive applications, we shifted 6 kT of material imported into the EU as Mg metal into the imports of Mg alloy category (corresponds to Mg alloy with 5.6 kT Mg content). We also added 2.8 kT of magnesium alloy stocks in the EU being drawn down in 2012. Stock building and de-stocking of metals is supply-, demand- and price-dependent and will change year-on-year; however, this level of stock draw-down sounded reasonable to industry sources.[17] This shift of material between import flows and the addition of a magnesium de-stocking flow meant that the uses of Mg metal in the EU, including in Al alloy production and pig iron desulphurisation, balanced with the amount of Mg metal imported.

Mg alloy casting and the finishing of cast components generates a large amount of Mg scrap. The extent of these losses generally depends on the size and geometry of the component being manufactured with higher losses associated with smaller, more complex parts such as used in electronic and power tool applications. The widely-accepted figure for the average efficiency of Mg alloy casting, in terms of Mg utilised in the finished product, is 50%.

The Mg alloy scrap generated by foundries can either be recycled internally (flow not shown but estimated by industry sources to equal approximately 9.3 kT of Mg content annually), sent to a third party for recycling (D.1.5) or disposed of (D.1.4). Foundries that disposed of part of their scrap Mg instead of recycling it all did so because of a lack of internal facilities to process Mg scrap heavily contaminated with cutting fluids and the prohibitive costs associated with transporting the scrap to recyclers, related to the low density of Mg.[18] Some Mg scrap from foundries is also exported to outside the EU. Using a mass balance approach, we estimated that 75% of the export of Mg waste and scrap (see Table 17 in Annex A) originates in foundries. The USA, where anti-dumping tariffs on Mg of Chinese origin inflate the prices paid for Mg from other regions, is the biggest recipient of the EU's exported Mg waste and scrap.

Mg scrap from foundries such as scrap castings and biscuits typically have a value to recyclers: as they have a known composition, relatively low surface area to weight ratio and are generated in high volumes. There are also other classes of foundry magnesium scrap such as those contaminated with other metals or cutting liquids, highly oxidised materials

[16] Industry source 8

[17] Industry source 18

[18] Industry sources 3 and 5

and residues from the melting processes accepted by magnesium recyclers.[19] As part of this research we identified a handful of magnesium recyclers in the EU including Magnesium Elektron (Czech Republic), Salgo (Hungary), Realalloy (Germany) and Magontec (Germany). Their combined processing capacity was estimated, by a variety of industry sources, to be in the range 35-45 kT.[20] They almost exclusively process new scrap, both EU generated (D.1.5) and imported from outside the EU (C.1.4), with very few examples given of EoL Mg scrap recycling given in interviews.

Demand for cast Mg alloy components is dominated by the automotive sector, accounting for an estimated 85% of the castings produced and imported into the EU.[21] We have assumed that the remaining 15% is accounted for by applications of Mg cast components in power tools and electronic equipment. There are many other small, specialist applications of Mg cast components, e.g. in aerospace and the defence sector, but these have not been dealt with separately in this flow analysis: it can be assumed that they are covered by the non-automotive Mg casting flows (see Section 0).

4.1.2 Discrepancies and uncertainties encountered in the sub-flow

Mapping this sub-flow relied on trade statistics, more than most. These were generally taken 'as is', though in some cases an assumption was made concerning the proportion of a particular trade to be allocated to a number of flows. We also assumed that approximately 10% of the Mg metal imported into the EU, or 6 kT, was in fact mis-categorised Mg alloy, and that there was 2.8 kT of Mg alloy stock draw-down in the EU in 2012. These decisions were made based on consideration of how to meet the downstream demand for Mg alloy castings.

The re-export of Mg alloys (C.1.2) depicted in the flow chart (Figure 8) as happening before the Mg alloy production step might be misleading. This trade code could also be capturing the export of secondary Mg alloy ingots produced by Mg recyclers but not sold back to EU foundries.

As described in Table 1, the major assumptions made concerning this sub-flow are related to melt losses. Conversely, we were able to obtain estimates from multiple sources related to the primary and secondary production of Mg alloys in the EU.

4.1.3 Key findings from the sub-flow

- 72.4 kT of the Mg in primary and processed material as well as in products (including semi-finished articles) imported into the EU is captured in this sub-flow.
- Of that, 52.2 kT ends up in Mg alloy castings used in EU based manufacturing, 15.1 kT ends up as processing or manufacturing waste and 8.1 kT is exported in product or processed material form.
- A 3% mismatch at the Mg casting stage of the sub-flow could indicate that EU stocks of Mg alloy were drawn down in 2012.
  The nature of die-casting processes means that it is inevitable that new Mg scrap will be generated and that, because of the Mg recycling capacity in the EU and demand for high grade scrap abroad, the functional recycling of this material is high.

---

[19] Description of different classes of Mg scrap and derivation of the 50% losses associated with Mg die-casting: http://library.nmlindia.org/FullText/MT20027.pdf

[20] Industry sources 6, 8, 10, 16 and 18

[21] Industry sources 6, 16 and 18

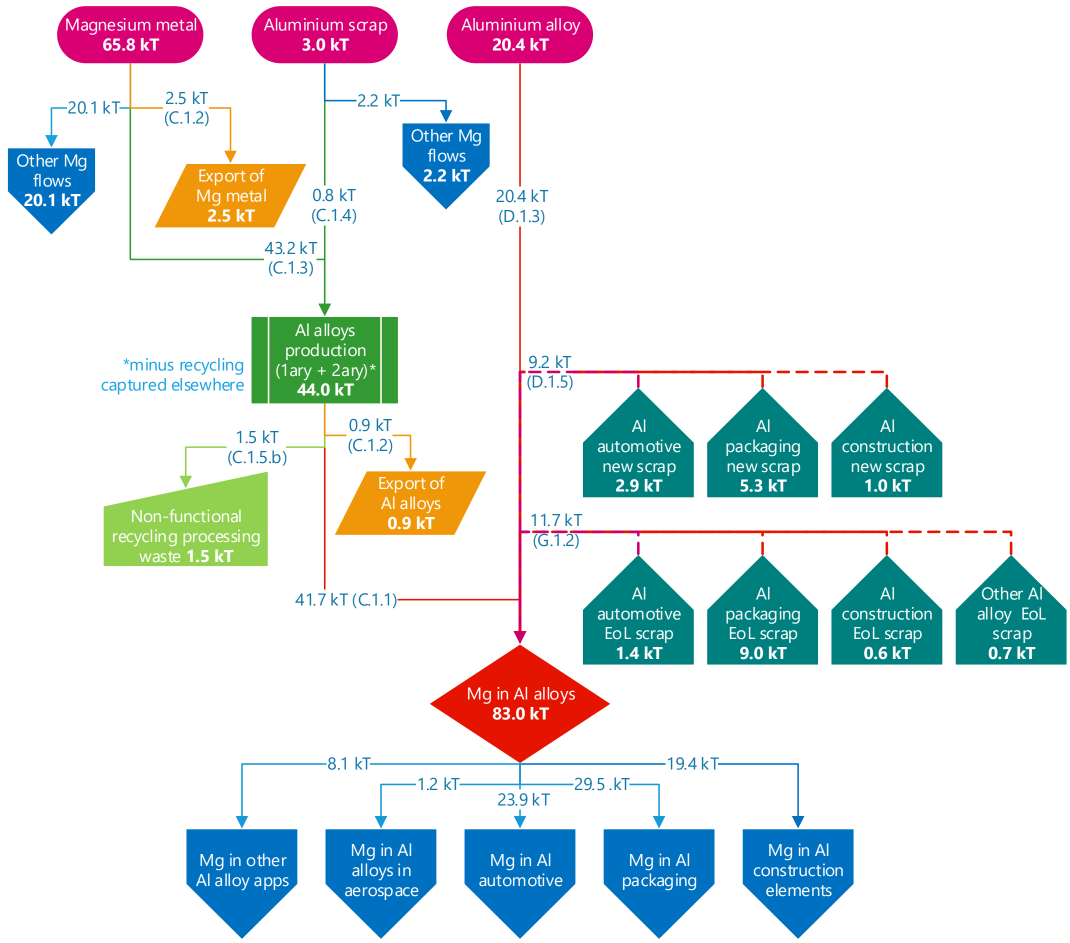
Table 1: Sources and calculations used to derive the material flows upstream of Mg's use in Mg alloy casting applications. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
C.1.1	EU produced Mg alloys used in the EU	3.9 kT of 1ary production and 40.3 kT of 2ary production identified. Assumed melt losses associated with EU derived and imported scrap to be 10%. Industry sources (8, 10 & 16) confirmed that 2ary production in the EU is in right range (35-45 kT).	44.2 kT
C.1.2	Export of Mg alloys	HS 810419, Table 15	6.1 kT
C.1.3	Import of Mg metal for use in 1ary and 2ary Mg alloy production	HS 810411, Table 12. Share of this trade flow allocated here determined by mass balance and confirmed to be in right range (3-5 kT) by industry source 8.	3.9 kT
C.1.4	Import of scrap Mg	HS 810420, Table 16	2.8 KT
C.1.5	Disposal of processing waste from Mg alloy production	2-5% melt loss associated with 1ary Mg remelting, 10% more typical for clean new scrap. Estimated 2/3 processing waste disposed, 1//3 functionally recycled.	1.7 kT
C.1.5.b	Functional recycling of processing waste from Mg alloy production	Some recyclers process skimmings and other high Mg slags (20-60% Mg content) to recover the Mg. Estimated 2/3 processing waste disposed, 1/3 functionally recycled.	0.8 kT
C.1.6	Export of processing waste from Mg alloy production	HS 810420, Table 17. 25% of this trade flow allocated here, the rest to D.1.6 below.	2.8 kT
D.1.1.b	EU produced Mg alloy castings used in the EU	Calculated via mass balance. Also made sure it was compatible to the amount of Mg castings expected in motor vehicles.	49.2 kT
D.1.2	Export of Mg alloy castings	HS 810490, Table 21. Average Mg alloy composition taken as 93% Mg, Table 35.	2.0 kT
D.1.3	Import of Mg alloy	HS 810419, Table 14. Average Mg alloy composition taken as 93% Mg, Table 35.	56.0 kT
D.1.3	Import of cast Mg components	HS 810490, Table 20. Average Mg alloy composition taken as 93% Mg, Table 35. 85% to automotive applications and 15% to non-automotive applications based on input from industry sources (6,16,18).	4.1 kT
D.1.4	Disposal of manufacturing waste from Mg alloy casting	Based on triangulation of information from several industry sources (5, 6, 16, 18)	2.3 kT
D.1.5	Functional recycling of manufacturing waste from Mg alloy casting	Based on triangulation of information from industry sources (6, 8, 10, 16, 18). Figure excludes internal recycling carried out by the foundries estimated by industry sources to be roughly 9.3 kT (of Mg content).	41.9 kT
D.1.6	Export of manufacturing waste from Mg alloy casting	HS 810420, Table 17. 75% of this trade flow allocated here, the rest to C.1.5 above.	8.3 kT

4.2 Flows upstream of Mg's use in Al alloys

A map of the flows upstream of Mg's use in Al alloys is shown in Figure 9. These flows are also depicted in the Sankey diagram in Figure 27. The flows are labelled with codes (C.1.3, D.1.2 etc.) used to refer to them in the text. The sources and calculations used to derive each flow are listed in Table 2.

Figure 9: Map of flows upstream of Mg's use in Al alloys



4.2.1 High level description of the sub-flow

The main applications of Al alloys in the EU are shown at the bottom of Figure 9. Mg is used to increase the strength of Al, both for non-heat-treatable alloys (5xxx series) and the heat-treatable Mg_2Si alloys (6xxx series). Mg is also used in the heat-treatable 2xxx and 7xxx series alloys. The composition and typical applications of some of these alloys and others referred to in this report are listed in Table 44. We have included all aluminium in our definition Al alloys, even if much of this has no or very low Mg content.

This section focuses on the production and import of Al alloys into the EU. For discussion on the manufacturing, use and EoL fates of the products made from these alloys see the sections covering downstream Mg flows, specifically Sections 4.3, 4.5, 4.6, 4.7 and 4.8. The same sections should be referred to for more information on the secondary material originating from the functional recycling of both new (D.1.5) and EoL (G.1.2) Al scrap downstream from this sub-flow.

According to World Aluminium's Global Aluminium Flow 2012 there is approximately equal amounts of primary and secondary Al ingot production in Europe (see Table 41).[22] However, there is 40% less primary than secondary unwrought Al alloy production reported for the EU in 2012 in Prodcom (see Table 36). This would suggest either that a higher proportion of primary Al ingots is exported from the EU, relative to secondary ingots, or that there is more secondary Al production in the EU than the wider European region. Either way, to avoid double counting it was critical that the functional recycling captured downstream (D.1.5 and G.1.2) was subtracted from the overall secondary production.

Al alloy production is the main application for the Mg metal imported into the EU (C.1.3), accounting for 66% of this flow. The remainder of the Al scrap import flow not already allocated to the recycling stages of downstream Al alloy applications (F.1.2) was also allocated as an input to the Al alloy production stage (C.1.4). We have considered two scenarios for the processing of Al scrap in the EU: either it is refined, a process during which the majority of Mg is removed, or it is remelted, with Mg loss minimised, to produce the same, or a similar, alloy. As a degree of certainty regarding the composition of the inputs is required for remelting, whether we allocated the flow to a refining or remelting process depended largely on the nature of the scrap flow.

Oxygen will preferentially react with Mg, compared to with Al and other alloying elements. This reactivity makes it one of the easiest impurities to remove from Al during the refining of secondary material. 'Demagging', as the Mg removal step is commonly referred to, is usually carried out with chlorine gas, though fluorine gas or solid salts such as AlF_3, $MgCl_2$, and KCl can also be used.[23] Typically Mg content is reduced from 0.5% to 0.1% during demagging, although this also depends on the process inputs and product specification.[24] The removed Mg ends up in the salt slag, typically recycled in the EU to recover the Al and salt it contains. An oxide residue, containing Mg amongst other elements, is left over after salt slag recycling and can be used in cement production, for aggregates and in mineral wool production.[25] This constitutes a non-functional recycling of Mg (C.1.5.b).

If the output alloy specification requires more Mg than present in the demagged Al, extra Mg - typically in the form of Mg metal ingots - will be added back into the melt in a controlled manner. Refined secondary Al is usually used for casting applications, given the greater tolerance these applications have towards difficult to remove impurities. Based on typical Mg concentrations in these alloys, ranging from 0.1% in most Al-Si alloys to 8.5% where additional strength and hardness is required (e.g. alloys 260 (0.2-0.5% Mg), 290 (0.5-0.65% Mg) and 518 (7.5-8.5% Mg))[26], we have estimated that Mg consumption is equal to 0.3% of the total secondary Al production. For primary Al production, we have estimated that 9kg of Mg is used per tonne of Al output, based on the average Mg composition of Al calculated in Table 35 (i.e. 0.9%).

---

[22] http://www.world-aluminium.org/statistics/

[23] Final Report on Refining Technologies of Aluminum, S. Bell B. Davis, A. Javaid and E. Essadiqi, Report No. 2003-21(CF), 2003 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/mineralsmetals/pdf/mms-smm/busi-indu/rad-rad/pdf/2003-21(cf)cc-eng.pdf)

[24] Chapter 12.8 on Secondary Aluminium Operations (https://www3.epa.gov/ttnchie1/ap42/ch12/final/c12s08.pdf)

[25] About the reclamation of Aluminium salt slag / salt cake / black dross (Dr. S. Buntenbach, G. Merker, Dr. K.-H. Bruch)

[26] Worldwide Guide to Equivalent Nonferrous Metals and Alloys, Editor Fran Cverna, ASM International, 2001

Some of the Al alloy recycling captured in flows D.1.5 and G.1.2 have been allocated to remelting operations, rather than refining. These processes are described further in the chapters concerned with Al alloys' downstream applications (4.3, 4.5, 4.6, 4.7 and 4.8).

Table 2: Sources and calculations used to derive the material flows upstream of Mg's use in Al alloys. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
C.1.1	Mg in Al alloys production sold in the EU	Used data from World Aluminium, Table 41. Subtracted secondary Al production captured in D.1.5 and G.1.2. Used estimated Mg content of 1^{ary} Al (0.9%)† and 2^{ary} Al (0.3%)‡.	41.7 kT
C.1.2	Mg in Mg metal exports from the EU (re-export)	HS 810411, Table 13	2.5 kT
C.1.2	Mg in Al alloys exports from the EU	Based on Prodcom statistics, Table 36, and an estimated Mg content of 0.4%: based on weighted average of estimated Mg content of 1^{ary} Al (0.9%)† and 2^{ary} Al (0.3%)‡.	0.9 kT
C.1.3	Mg in Mg metal imports into the EU	HS 810411, Table 12. Share of this trade flow allocated here based on World Aluminium data, Table 41, and the estimated Mg content of 1^{ary} Al (0.9%)† and 2^{ary} Al (0.3%)‡.	43.2 kT
C.1.4	Mg in waste and scrap Al imports into the EU	HS 760200, Table 22. Allocated 30% of this flow here, the remainder is captured in flows F.1.2 in various downstream Al applications.	0.8 kT
C.1.5.b	Mg in Al alloy waste in the EU sent for reprocessing	Estimated Mg melt losses of 2% in 1^{ary} Al production and 7% in 2^{ary} Al production and that all salt slag in the EU is recycled. Confirmed by industry source 16.	1.5 kT
D.1.3	Mg in Al alloy imports into the EU	Based on Prodcom statistics, Table 36 and an estimated Mg content of 1^{ary} Al (0.9%)†.	20.4 kT
D.1.5	Mg in Al alloy manufacturing waste in the EU sent for reprocessing	These flows are captured in Sections 4.3, 4.5 and 4.6.	9.0 KT
G.1.2	Mg in secondary material from recycling EoL Al alloys	These flows are captured in Sections 4.3, 4.5, 4.6 and 4.8.	11.7 kT

†For derivation of 0.9% average Mg content in 1ary Al see Table 42, ‡Based on average Mg content of casting alloys,[27] which are the main use of secondary Al, due to their higher impurity tolerances.

[27] http://stenaaluminium.com/PageFiles/8085/CAST%20ALLOYS%20IN%20ALUMINIUM%202013.pdf

4.2.2 Discrepancies and uncertainties encountered in the sub-flow

There is a slight mismatch (1%) between the Mg used in Al alloy production in the EU (83.0 kT) and the identified uses of those alloys (82.1 kT). Given the uncertainties associated with our reliance on trade data and estimated average Mg contents of Al alloys, this level of mismatch across a stage is not unexpected.

The estimation of typical Mg consumption for both primary and secondary Al refining is the greatest source of uncertainty in this flow, especially given that use in Al alloy production accounts for 22% of the Mg imported into the EU.

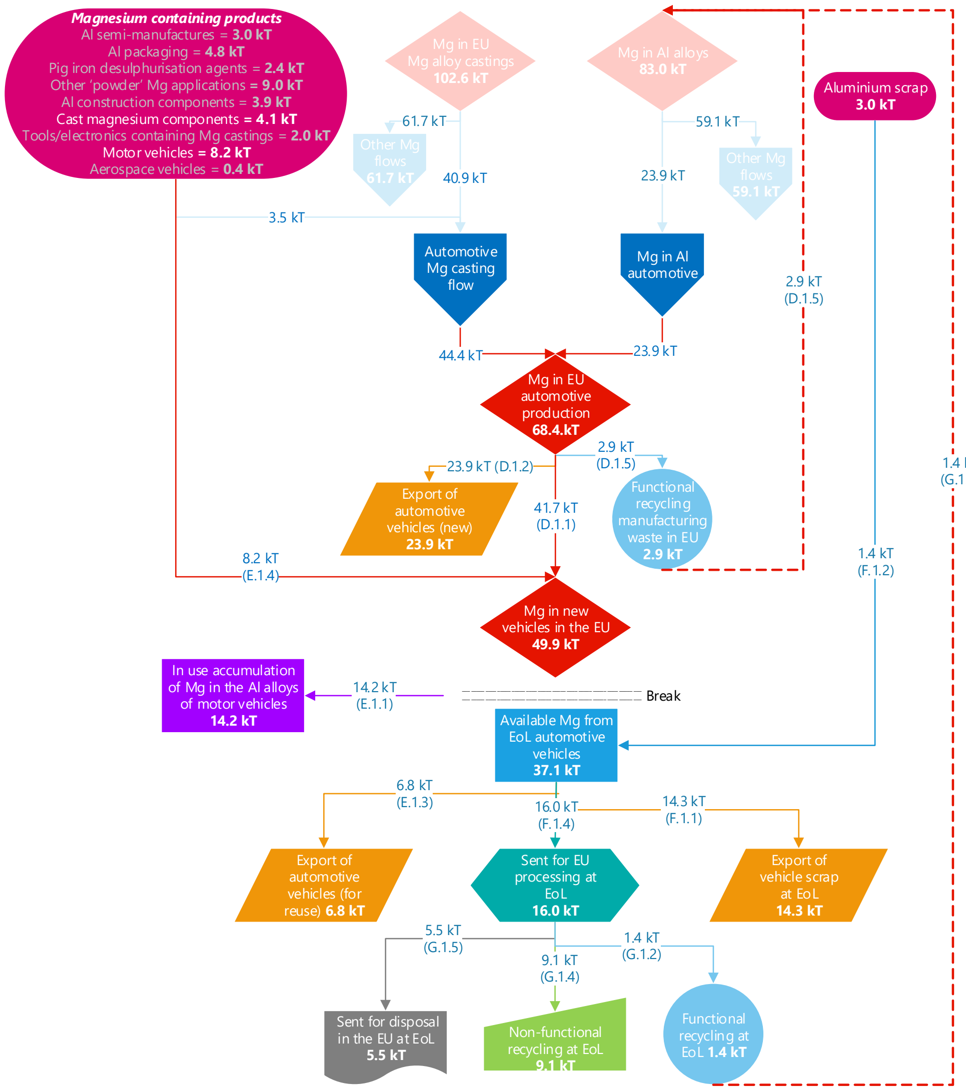
4.2.3 Key findings from the sub-flow

- Primary and secondary production of Al alloys is roughly equal in Europe.
- Approximately half of Al alloy secondary production is captured in this flow and the rest in the downstream flows of Al alloys.
- Al alloy production in the EU accounts for 22% of the Mg imported into the EU. A further 12% of the imported Mg is already in Al alloy form (including scrap and processed material).
- Mg removed from Al during refining ends up in the salt slag that is processed to recover the Al and salt, leaving the Mg in an oxide residue. This oxide residue can be used to produce cement, aggregates and mineral wool - all forms of non-functional Mg recycling.

4.3 Mg in automotive applications: use and EoL situation

Figure 10 is a map of the flows downstream of Mg's use in automotive Mg alloy castings. These flows are also depicted in the Sankey diagram in Figure 28. The flows are labelled with codes (C.1.3, D.1.2 etc.) used to refer to them in the text. Some upstream flows, as already covered in Chapters 4.1 and 4.2, are shown (faded out) for reference. The sources and calculations used to derive each flow are listed in Table 3.

Figure 10: Map of downstream flows related to Mg's use in automotive applications



4.3.1 High level description of the sub-flow

The use of Mg in automotive applications was by far the largest use of Mg in the EU in 2012 at approximately 50 kT. As well as consuming 85% of the Mg castings produced and imported into the EU (flows D.1.1 and D.1.3 respectively), the automotive sector is using an increasing amount of Al in vehicle production, particularly of rolled Al sheet which can have a high Mg content (see Table 45). Between 2002 and 2012 the overall Al content of a typical vehicle increased by approximately 20%, whilst the amount of rolled Al in vehicles nearly doubled.[28] Data from the EAA reports were used to derive a typical amount of Mg contained in the Al alloys in vehicles produced in 2012 and reaching their EoL in 2012 (produced in 2002); see Table 45 to Table 47.

Reliable data on the typical weight of Mg cast components in typical vehicles could not be obtained. Industry experts were invited to provide estimates, but the range of values offered was too wide (between 2 and 10 kg per vehicle) to be of use. One literature source from the USA estimated a Mg weight per vehicle of 4.1 kg, in a typical 2002 vehicle, as well as providing a summary of the weight and weight saving potential of using Mg in various vehicle components.[29] However, because of the differences in Mg casting utilisation across vehicles, ranging from none to 10s of kgs, we took a different approach to estimating a typical Mg content per vehicle:

- Using good quality data on vehicle production, import and export from ACEA30.
- Assuming Mg use in light commercial vehicles, trucks and buses was negligible compared to in passenger vehicles.
- Dividing the weight of Mg castings used in automotive applications in the EU (44.4 kT, D.1.1b + D.1.3) by the number of vehicles produced in the EU.

This approach allowed us to derive the average weight of Mg in Mg alloy castings in a typical vehicle to be 2.7 kg in 2012. Assuming the growth in Mg component use mirrored that of Al, we also estimated that for vehicles produced in 2002 the average Mg content per vehicle was 2.2 kg.

The difference in Mg content between cars produced in 2012 and those reaching their EoL in that year was key to estimating the in-use accumulation of Mg in the EU's vehicles. The ELV waste statistics compiled in Eurostat were also used (see Annex B) though a correction factor had to be applied to reallocate the vehicles described as having 'unknown whereabouts' at their EoL (see Figure 11). This correction factor required the assumption that the EoL treatment of vehicles in 2012 was similar to in 2013 and that the 3.6 million vehicles unaccounted for at EoL were distributed proportionally (81:19) between 'ELV-reporting' and 'Extra-EU28 used car export'.

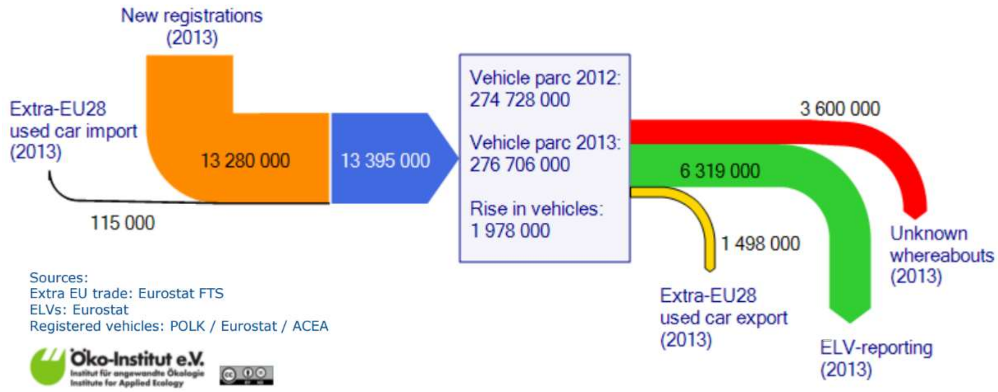
---

[28] EAA reports: Aluminium penetration in cars, Final Report, March 13, 2012 (Public version) by Ducker worldwide and Aluminium content in cars, Summary Report , June 2016 (Public version) by Ducker worldwide

[29] Magnesium and its alloys applications in automotive industry, MK Kulekci, Int J Adv Manuf Technol (2008) 39:851–865 (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.463.133&rep=rep1&type=pdf)

[30] http://www.acea.be/publications/article/acea-pocket-guide

Figure 11: Summary of ELV reporting, registered vehicles, imported and exported vehicles in the EU in 2013



Source: Reproduced from presentation on 'The ELV Directive and its implementation', B Lorz, UN-ECE conference March 2017.[31]

Using this approach we estimated that 18% of vehicles treated at EoL or exported from the EU in 2012 were in fact exported from the EU for reuse. The remainder were processed, or at least partly processed, in the EU. The amount of Mg in ELV-derived scrap exported from the EU (F.1.1) was similar to that processed in the EU (F.1.4). This scrap export flow can partly be attributed to demand created by the attractive economics of hand sorting non-ferrous scrap in low wage economies such as China, India and Pakistan.

At EoL, vehicles in the EU should be processed at Authorised Treatment Facilities (ATFs). Some of the 'unknown whereabouts' vehicles are likely to be being dismantled illegally at dealers and repair shops. At ATFs, vehicles are depolluted and all fluids removed according to the ELV Directive. In addition, some components might be recovered for reuse or dismantled and segregated by material or alloy in order to extract a higher value from the vehicle. Finally, the remaining wreck is shredded and magnetic and density separation techniques used to separate the ferrous, non-ferrous and non-metallic shredded material. Non-ferrous outputs of shredding and dense-media separation plants, such as zorba and twitch respectively, are used as inputs for secondary Al production by Al refiners. We have estimated that 20% of the Mg in ELVs ends up in dismantled components and 80% in the non-ferrous shredder fraction.[32]

The split between dismantling and shredding is important because it affects the options available for the further processing of the Mg containing ELV scrap. Mg-containing dismantled components, assumed to all be of Al alloys, are more likely to be segregated and sorted by alloy type and processed by remelters who will try and retain as much of the Mg as possible. Mg-containing but predominantly Al shredded material is, on the other hand, exclusively processed by refiners who remove all the Mg in order to produce low Mg casting alloys. For details of the estimates used to allocate the recycling the fate of the Mg in ELVs processed in the EU see flows F.1.1 onwards in Table 3.

[31] https://www.unece.org/fileadmin/DAM/trans/doc/2017/itc/UNEP_05_European_Commission_-_UN_ECE200217SHORT.pdf

[32] Current Al component dismantling estimated to include 100% of wheels, 10% of closures, 50% of bumpers and crash boxes and 50% of engine blocks in 'Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements', Environmental Science & Technology · March 2014, by AN Løvik, R, Modaresi and DB Müller

Table 3: Sources and calculations used to derive the downstream material flows of Mg's use in automotive applications. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in vehicles: sold production in the EU	Registrations - Imports = 10,077,156 cars (ACEA pocket handbooks) with 4.14 kg of Mg per car (Table 47). Assumed that Mg in light commercial vehicles, trucks and buses was negligible.	41.7 kT
D.1.2	Mg in vehicles: exports from EU	5,764,041 cars exported in 2012 (ACEA pocket handbooks)	23.9 KT
D.1.5	Mg in vehicle manufacturing waste in the EU sent for reprocessing	4.6% (35% x 13%) of Mg in cars is in wrought Al sheet (Table 45). Waste associated with pressing and stamping this sheet is ca.50%.† Assumed that all waste associated with cast components captured in foundries.	2.9 kT
E.1.1	In-use accumulation of Mg in vehicles in the EU	Difference between the Mg used in new vehicles sold in the EU in 2012 and that available from EU vehicles reaching their EoL in 2012.	14.2 kT
E.1.3	Mg in exported vehicles for reuse	Based on Öko-Institut workup of Eurostat data and assuming the EoL vehicles they categorise as 'unknown whereabouts' are 81% processed in the EU and 19% exported for reuse.‡	6.8 kT
E.1.4	Mg in vehicles imported into EU	1,976,748 cars imported in 2012 (ACEA pocket handbooks)	8.2 kT
F.1.1	Mg in EoL vehicle scrap exported from the EU	Estimated that 20% of the Mg in ELVs ends up in dismantled components and 80% in the non-ferrous shredder fraction. <u>Dismantled components:</u> 320,520 T of ELV export reported in Eurostat. Adding in 81% of EoL vehicles of 'unknown whereabouts' identified by Öko-Institut gives 468,408 T. Average vehicle weight assumed to be 1.4 T. <u>Non-ferrous shredder fraction</u>: HS 760200, Table 23. Allocated 44% of this flow to ELVs. Typical Mg content of flow is 2.1%.††	14.3 kT
F.1.2	Mg in EoL vehicles imported into the EU	HS 760200, Table 22. Allocated 44% of this flow here, the remainder is captured in other F.1.2 flows and flow C.1.4 upstream of Al alloys.*	1.4 kT
F.1.4	Mg in EoL vehicles sent for recycling in the EU	<u>Dismantled components:</u> 337,370 T of metal component recycling, including contribution from EoL vehicles of 'unknown whereabouts', Table 33. Dismantled components have higher non-ferrous fraction than shredded material. Mass balance used to allocate 14% of this flow to aluminium with 1% Mg content. <u>Non-ferrous shredder fraction</u>: From mass balance, however, this flow calculated to be	16.0 kT

		9.9 kT (corresponding to Mg concentration 3.5% in non-ferrous shredder fraction)	
G.1.2	Mg in secondary material from recycling EoL vehicles	Assumed 1/3 of dismantled material and imported scrap goes to remelters.‡‡ Mg melt losses of 1/3 associated with remelting Al alloys (industry source 7). Assumed all non-ferrous shredder residue sent to refiners.	1.4 kT
G.1.4	Mg from EoL vehicles to non-functional recycling in the EU	All Mg in Al sent to refiners ends up in salt slag, as does a 1/3 of that sent to remelters. Assumed that 75% of oxide residues from salt slag recycling are non-functionally recycled and 25% disposed of. Of that non-functionally recycled, the processing losses assumed to be 25%.	9.1 kT
G.1.5	Mg from EoL vehicles sent for disposal in the EU	Non-recycled oxide residues from salt slag recycling and losses from the non-functional recycling of oxide residues allocated to this disposal flow.	5.5 kT

† Design – Aluminium design for cost optimization (http://european-aluminium.eu/media/1510/aam-design-4-design-for-cost-optimization.pdf)
‡ https://www.unece.org/fileadmin/DAM/trans/doc/2017/itc/UNEP_05_European_Commission_-_UN_ECE200217SHORT.pdf
** 44% based on sources of Aluminium scrap figure in End-of-waste Criteria for Aluminium and Aluminium ††Alloy Scrap: Technical Proposals, JRC, 2010 (http://ftp.jrc.es/EURdoc/JRC58527.pdf)*
Separation of Non-ferrous Fractions of Shredded End-of-life Vehicles for Valorising its Alloys (http://avestia.com/MMME2014_Proceedings/papers/77.pdf)
‡‡ Automotive Aluminum Recycling at End of Life A Grave-to-Gate Analysis, US, 2016 (http://www.drivealuminum.org/wp-content/uploads/2016/06/Final-Report-Automotive-Aluminum-Recycling-at-End-of-Life-A-Grave-to-Gate-Analysis.pdf)

4.3.2 Discrepancies and uncertainties encountered in the sub-flow

Without reliable data on the typical amount of magnesium in a European vehicle we had to work backwards from what we knew, i.e. the production of vehicles in the EU and the production of Mg alloy castings. Nevertheless, the value obtained for the amount of Mg in the Mg castings in 2012 vehicles (2.7 kg) was in the range of estimates provided by industry sources, although very near the bottom of that range.

There are also uncertainties stemming from the EoL vehicles whose export for reuse or ELV processing in the EU is missing from official statistics. For some flows (F.1.1 and F.1.2) it was possible to allocate a proportion of the trade in Al waste and scrap to ELVs instead of using the ELV statistics in Eurostat. Apparent differences in the interpretation and reporting of ELV export and treatment by Member States, see Annex B, meant that we took the overall reliability of the ELV data to be relatively low.

The largest uncertainties in this flow were related to the processing of ELVs and what happens to the Mg in dismantled components versus shredded material. The extent of dismantling varies between Member States and depends on the price of different types of metal scrap and how it relates to the labour costs associated with dismantling. At 9% (G.1.1/F.1.4), the amount of EoL functional Mg recycling derived for this flow is low, as most of the Mg-containing material is assumed to be sent to refiners.

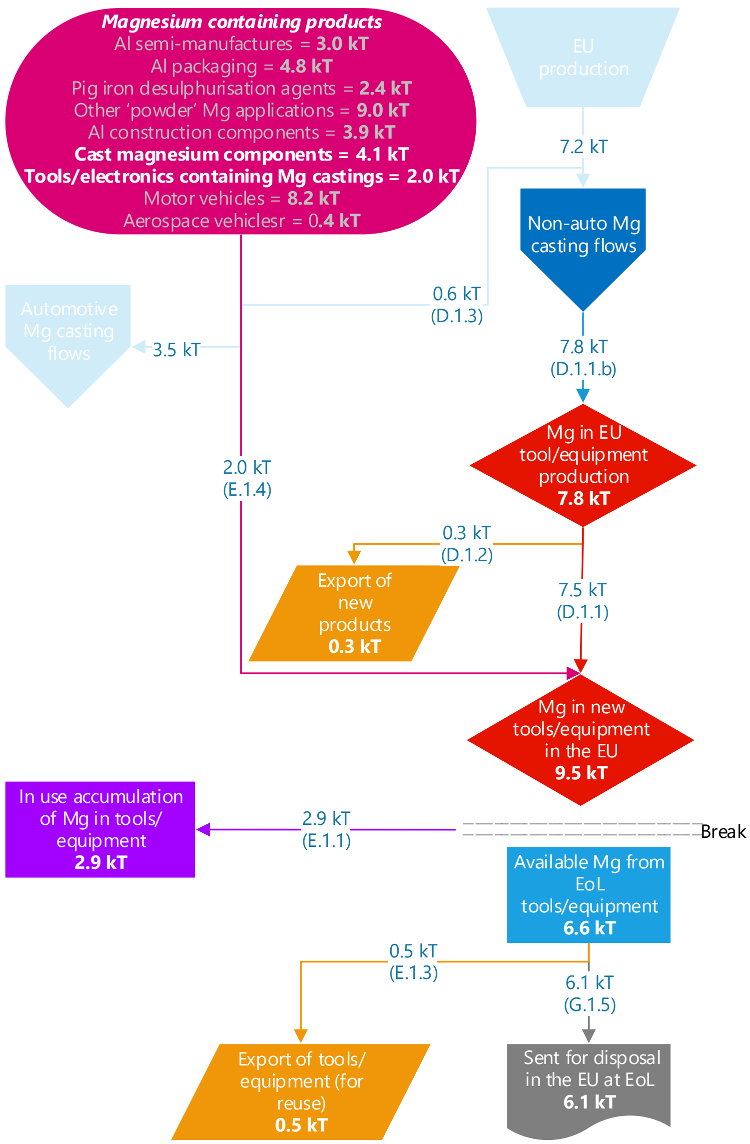
4.3.3 Key findings from the sub-flow

- There is functional recycling of new and old Mg-containing scrap associated with the vehicles flow.
- The amount of Mg in vehicles is constrained by the amount of Mg alloy castings produced and imported into the EU.
- The amount of Mg in vehicles increased by 32% between 2002 and 2012, driven by a 55% increase in Mg use in the Al alloys in vehicles.
- The extent of Al and Mg component dismantling from ELVs has consequences for the EoL functional recycling of Mg as it affects the proportion of scrap going to Al remelters versus refiners.
- There is significant in-use accumulation of Mg in vehicles in the EU as a result of cars getting bigger, there being more cars on the roads, and more Al and Mg alloys being used in car production.

4.4 Mg in non-automotive applications for Mg alloy castings: use and EoL situation

Figure 12 maps the flows downstream of Mg's use in non-automotive Mg alloy castings. These flows are also depicted in the Sankey diagram in Figure 28. The flows are labelled with codes used to refer to them in the text. Some upstream flows, as already covered in Chapters 4.1 and 4.2, are shown (faded out) for reference. The sources and calculations used to derive each flow are listed in Table 4.

Figure 12: Map of downstream flows related to Mg's use in non-automotive Mg casting applications



4.4.1 High level description of the sub-flow

Non-automotive applications account for approximately 15% of the Mg alloy castings produced and imported into the EU.[33] Non-automotive applications of Mg components can broadly be subdivided further into: tools and equipment, including chain saws, power tools and lawn mowers; and consumer electronics. The Mg-containing tools and equipment consumed in the EU are predominantly produced in the EU by companies such as Stihl and Husqvarna, whilst consumer electronics containing Mg are more likely to be imported from outside the EU, mainly Asia.

We estimated that approximately one third more Mg is going into tools, equipment and electronics put into garages and workshops across the EU than is available in the products reaching their EoL and actually being disposed of by their users. This number seemed reasonable to industry experts especially given that high-end tools and equipment, which are more likely to contain Mg, often last their users a lifetime if not more.

Table 4: Sources and calculations used to derive the downstream material flows of Mg's use in non-automotive casting applications. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in tools/equipment: sold production in the EU	D.1.2 subtracted from D.1.1.b	7.5 kT
D.1.1.b	Mg in castings: sold production in the EU	Calculated via mass balance with 15% of flow allocated to non-automotive applications (based on input from industry sources 6, 16 and 18).	7.8 kT
D.1.2	Mg in tools/equipment: exports from the EU	Used HS 843311 (lawn mowers) and HS 846781 (chain saws) as proxy measure for this flow. Assumed 0.5 kg Mg per lawn mower and 0.1 kg Mg per chain saw.	0.3 kT
E.1.1	In-use accumulation of Mg in tools/equipment in the EU	In-use lifetime of consumer electronics typically years and power tools typically decades. Estimate in-use accumulation equal to 1/3 of consumption to reflect user hoarding of products.	2.9 kT
E.1.3	Mg in exported tools/ equipment for reuse	No data available on exports for reuse but assume it is non-zero because Mg products likely to be at high end of market. 0.5 kT is an estimate.	0.5 kT
E.1.4	Mg in tools/equipment imported into the EU	Using HS 843311 and HS 846781 as proxy measure for this flow and assuming 0.5 kg Mg per lawn mower and 0.1 kg Mg per chain saw gives 2.26 kT. Rounded to nearest kT.	2.0 kT
G.1.5	Mg from EoL tools/ equipment sent for disposal in the EU	In lieu of further information we assumed a worst case scenario: that all these items are disposed of to landfill.	6.1 kT

[33] Industry sources 6, 16 and 18

Though only an indirect measure, we looked at the import and export into the EU of some products known to sometimes contain Mg castings, i.e. lawn mowers and chainsaws. There was significantly more of these products imported into the EU, mostly from China and the USA, than exported (see Table 24 to Table 27). We approximated an Mg content per product, well aware that many products are likely to contain no Mg at all. Neither did we try to look at consumer electronic trade flows as these are even more diverse in nature than the lawn mowers and chain saws. Nevertheless, we feel that the quantities allocated to the flows for non-automotive Mg castings are reasonable and, because they are small relative to other downstream flows, will not have a large impact on the overall material flow analysis for Mg.

4.4.2 Discrepancies and uncertainties encountered in the sub-flow

As this was a relatively small flow containing a diverse range of products we took the decision to rely on proxy metrics and estimates if there was no other data available (see Table 4). Due to the uncertainties this approach created, we were especially cautious when allocating the EoL fate of the Mg in these products. Instead of assuming that all or some proportion of the EoL products was sent to metal recycling facilities where the products would be shredded and the Mg accumulated in the non-ferrous shredder fraction, we assumed all the Mg in this flow ended up being disposed of. This decision reflects that we were not sufficiently confident in the underlying data to allocate any of this flow to functional or non-functional recycling.

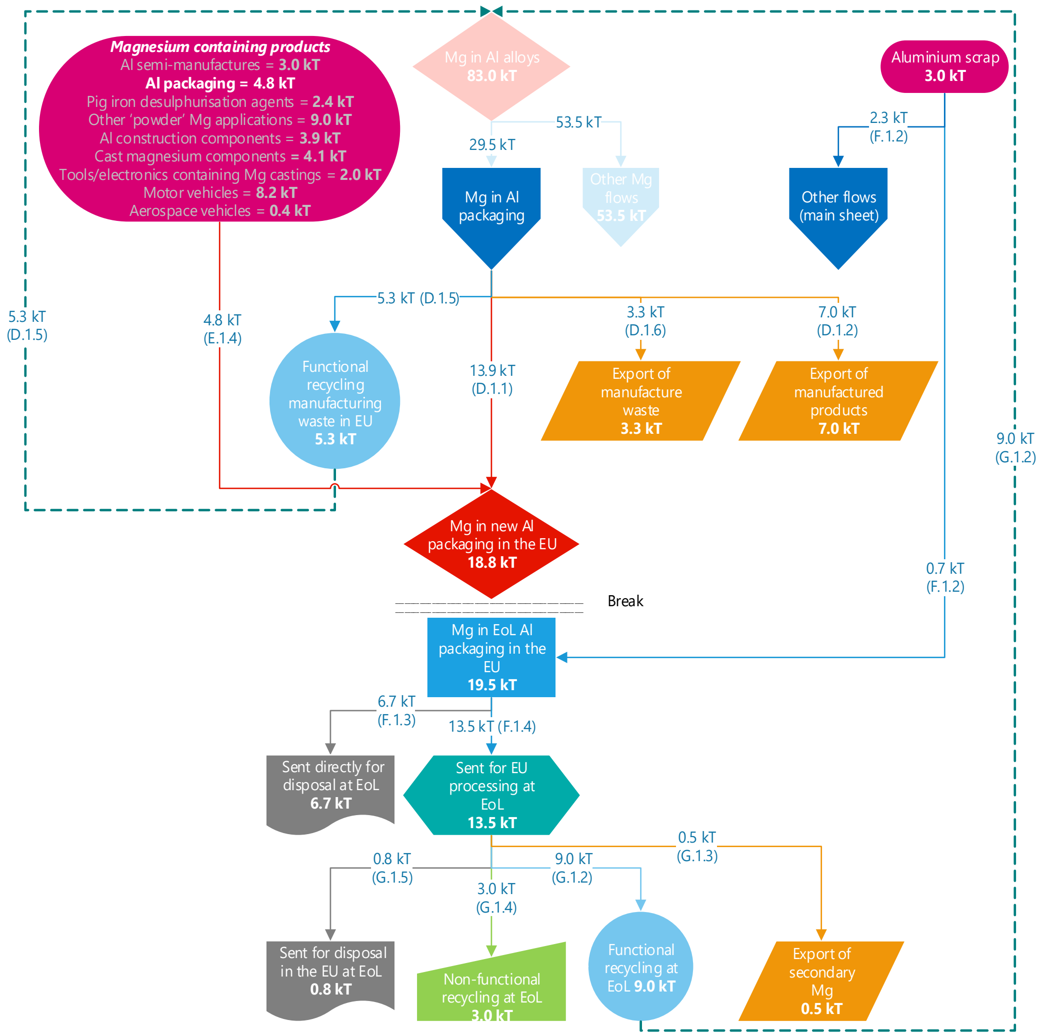
4.4.3 Key findings from the sub-flow

- 15% of Mg alloy castings are used in non-automotive applications.
- Approximately 80% of the EU's consumption of non-automotive Mg alloy castings are produced in the EU.
- We estimated that 1/3 more Mg was going into non-automotive Mg casting applications in the EU than in products being collected at their EoL in 2012.

4.5 Mg in Al alloy packaging applications: use and EoL situation

Figure 13 maps the flows downstream of Mg's use in Al packaging applications. These flows are also depicted in the Sankey diagram in Figure 29. The flows are labelled with codes used to refer to them in the text. Some upstream flows, as already covered in Chapters 4.1 and 4.2, are shown (faded out) for reference. The sources and calculations used to derive each flow are listed in Table 5.

Figure 13: Map of downstream flows related to Mg's use in Al packaging applications



4.5.1 High level description of the sub-flow

Al packaging is a major application of aluminium in Europe: 19% of the net shipments of Al products in Europe are packaging.[34] Al packaging is also a very important flow for Mg in the EU, in that it constitutes over three-quarters of the functional EoL recycling (G.1.2) we have

[34] Global Aluminium Flow Model 2012, World Aluminium

been able to identify for Mg. This is primarily because of the high turnover rate of Al packaging, with beverage cans potentially being recycled multiple times per year, and due to their relatively high collection rates: 70% for beverage cans and 45% for other Al packaging.[35] The estimate, based on a literature source (see Table 5), that the Mg melt losses associated with Al packaging recycling are one third, was also key to quantifying this flow. Unfortunately, we were unable to get EU aluminium industry sources to comment on this value. The non-functional recycling rate of the metal oxide residue from salt slag recycling was derived using the same method as in Section 4.3.

Many of the flows related to Al packaging, and other Mg in Al alloy applications covered below, were quantified using production-based splits (Table 42) and splits based on the breakdown of Al scrap sources (Table 44). These splits were then applied to either trade data or to the flows of Al between Europe and the rest of the world mapped in the Global Aluminium Flow 2012 produced by World Aluminium (see Table 41). A typical Mg content for the Al alloys used in Al packaging applications was also derived (see Table 38).

In the case of Al packaging, the approach of using splits applied to Al trade/material flows worked well and each stage of the flow balanced. It was therefore unnecessary to look in detail at more specific Al packaging related trade flows, such as those for products that are packed in Al.

Table 5: Sources and calculations used to derive the downstream material flows of Mg's use in Al packaging applications. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in Al packaging: sold production in the EU	Applied production split in Table 42, i.e. 19% packaging, to the 6,673 kT of European Al manufacturing throughput used in Europe, Table 41. Mg content as derived in Table 38, 1.1%.	13.9 kT
D.1.2	Mg in Al packaging: exports from the EU	Applied production split in Table 42, i.e. 19% packaging, to the 3,344 kT of European Al manufacturing throughput exported from Europe, Table 41. Mg content as derived in Table 38, 1.1%.	7.0 kT
D.1.5	Mg in Al packaging manufacturing waste in the EU sent for reprocessing	1,711 kT of European Al manufacturing throughput sent for scrap processing, Table 41. 28% of this flow allocated to packaging.* Mg content as derived in Table 38, 1.1%.	5.3 kT
D.1.6	Mg in Al packaging manufacture waste exports from the EU	HS 76020000. Total export from EU using this trade code in 2012 was 1,084 kT, Table 23. 28% of this flow allocated to packaging.*	3.3 kT
E.1.4	Mg in Al packaging imported into the EU	Applied production split in Table 42, i.e. 19% packaging, to the 2,310 kT of manufacturing imports into Europe, Table 41. Mg content = 1.1%.	4.8 kT

[35] EAA (http://www.european-aluminium.eu/) and Alupro (http://www.alupro.org.uk/)

F.1.2	Mg in EoL Al packaging imported into the EU	HS 76020000. Total import from EU using this trade code in 2012 was 321 kT, Table 22. 28% of this flow allocated to packaging.*	0.7 kT
F.1.3	Mg in Al packaging sent directly for disposal at EoL	30% of beverage cans and 55% of other Al packaging waste collected unsegregated at EoL (Industry source 12). Assumed all is disposed of.	6.7 kT
F.1.4	Mg in Al packaging EoL waste in the EU sent for reprocessing	4,372 kT of EoL Al from Europe sent for reprocessing in Europe, Table 41. 28% of this flow allocated to packaging.* Mg content = 1.1%.	13.5 kT
G.1.2	Mg in secondary material from recycling EoL Al packaging sent for use in the EU	Applied melt losses of 1/3 to Al packaging recycling which, because of collection rate, is predominantly EoL beverage cans.†	9.0 kT
G.1.3	Mg in secondary material from recycling EoL Al packaging exported	166 kT unwrought aluminium alloys in secondary form (excluding aluminium powders and flakes) exported from EU in 2012, Table 36. 28% of this flow allocated to packaging.*	0.5 kT
G.1.4	Mg from EoL Al packaging reprocessing to non-functional recycling in the EU	Mg melt losses from Al packaging recycling end up in salt slag. Assumed that 75% of oxide residues from salt slag recycling are non-functionally recycled and 25% disposed of. Of that non-functionally recycled, the processing losses assumed to be 25%.	3.0 kT
G.1.5	Mg from EoL Al packaging reprocessing sent for disposal in the EU	Non-recycled oxide residues from salt slag recycling and losses from the non-functional recycling of oxide residues allocated to this disposal flow.	0.8 kT

** 28% based on sources of Aluminium scrap figure in End-of-waste Criteria for Aluminium and Aluminium Alloy Scrap: Technical Proposals, JRC, 2010 (http://ftp.jrc.es/EURdoc/JRC58527.pdf)*
† Market dynamics, recycling and recovery of magnesium from aluminium alloy scrap: A.J. Gesing, S.K. Das

4.5.2 Discrepancies and uncertainties encountered in the sub-flow

The main uncertainties in this flow stem from the splits used to allocate certain proportions of the Al flows mapped in World Aluminium's Global Aluminium Flow 2012 to packaging versus other Al applications. For example, the production data in Table 42 is for Europe rather than the EU. Also the scrap sources are semi-grouped in Table 43 and the derivation of these numbers is unclear in the reference.

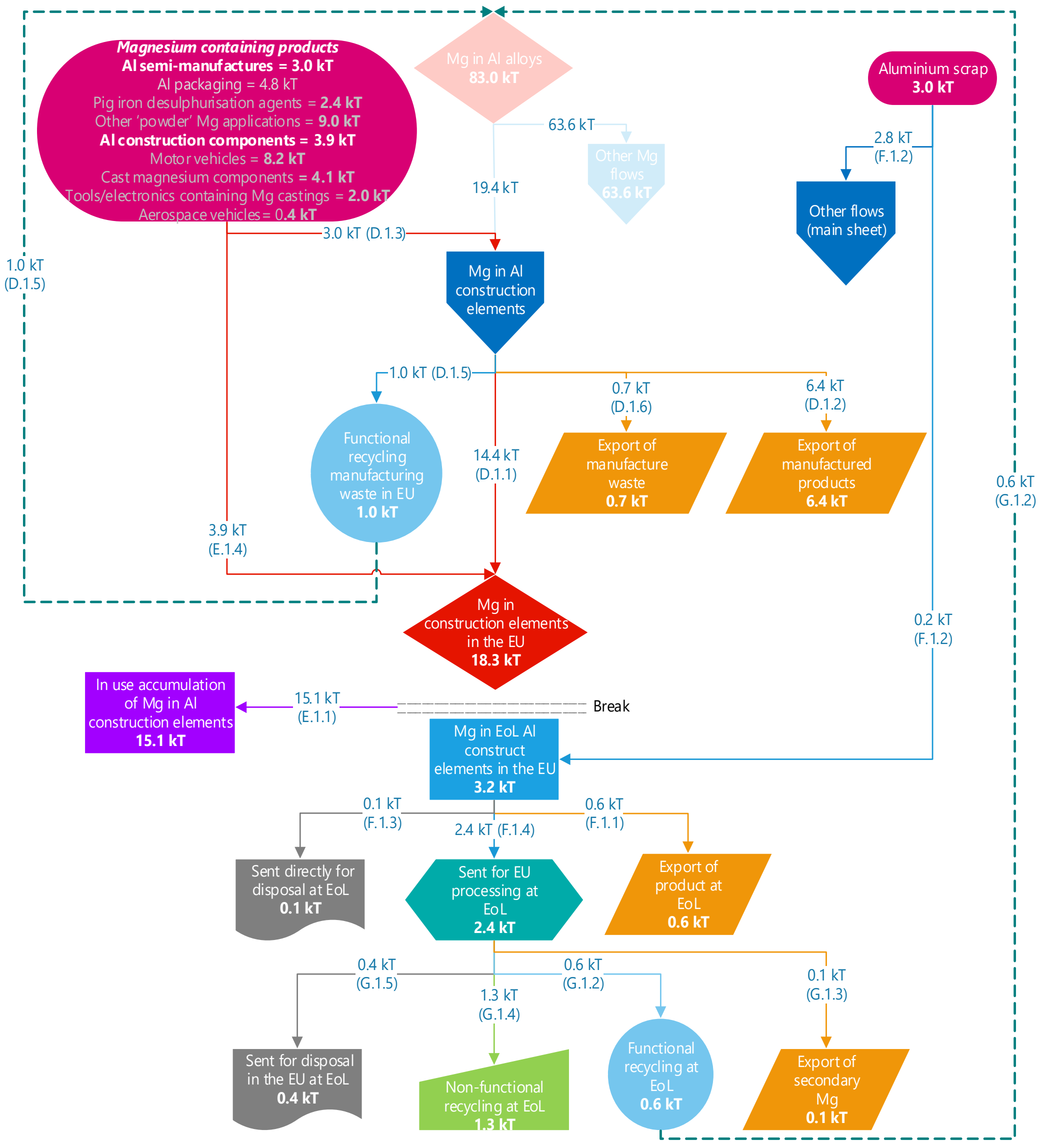
4.5.3 Key findings from the sub-flow

- 77% of the functional EoL Mg recycling identified in this study is associated with this Al packaging flow.
- Approximately 1/3 of the Al packaging produced in the EU is exported.
- The collection rate for Al beverage cans is 70% and that for other Al packaging is 45%.
- By weight, Al beverage cans make up 56% of all packaging produced in Europe.
- Mg melt losses associated with Al packaging recycling are 1/3.

4.6 Mg in Al alloy construction applications: use and EoL situation

A map of the flows downstream of Mg's use in Al construction applications is shown in Figure 14. These flows are also depicted in the Sankey diagram in Figure 30. The flows are labelled with codes used to refer to them in the text. Some upstream flows, as already covered in Chapters 4.1 and 4.2, are shown (faded out) for reference. The sources and calculations used to derive each flow are listed in Table 6.

Figure 14: Map of downstream flows related to Mg's use in Al construction applications

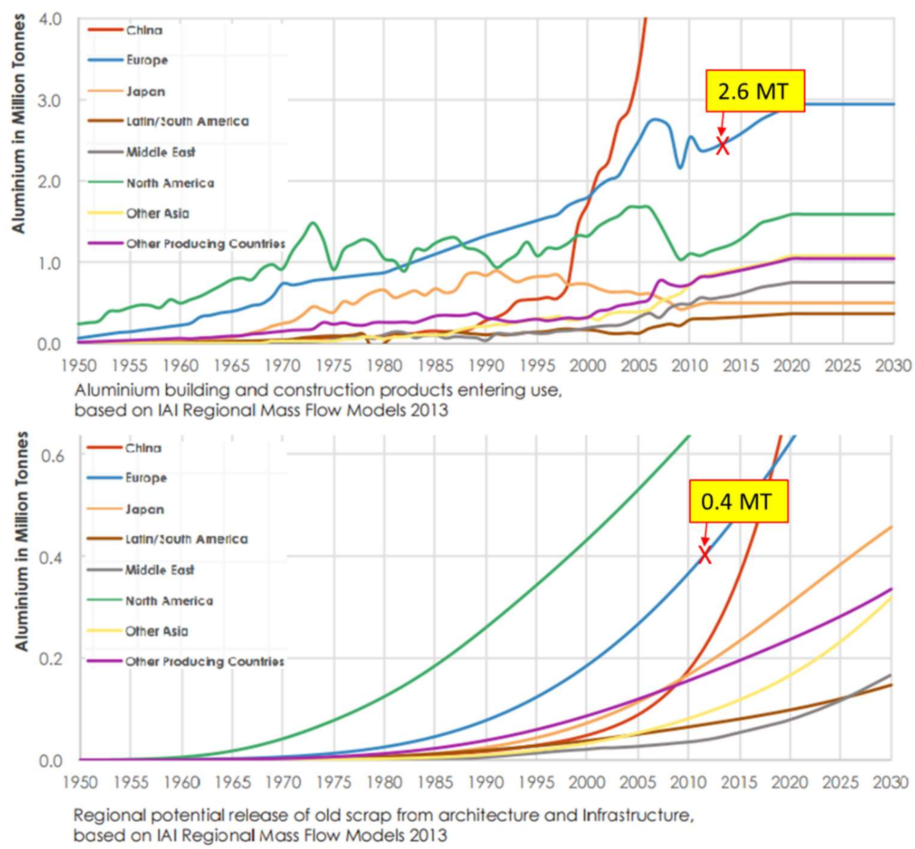


4.6.1 High level description of the sub-flow

It is estimated that three quarters of the Al ever produced is still in productive use today and that 30% of this is in building and construction applications.[36] This is a testament to the durability of aluminium construction components and the long lifetime of buildings, particularly high quality and civic buildings. Al alloy construction elements are used in roofing, windows, balconies, doors, internal fittings such as sinks and door handles as well as fencing and facades. Some of these applications, particularly where the Al alloy component has a structural function, can contain significant amounts of Mg. See Table 39 for our derivation of an average 0.8% Mg content in Al construction elements.

Even though the collection rate of Al construction elements during building demolition is high (approximately 95% in Europe[37]) the amount of the Al construction elements available at EoL in 2012 was only about 15% of that used in new construction projects in the same year (see Figure 15). This results in a significant in-use accumulation of Mg associated with this flow, circa 15 kT (E.1.1).

Figure 15: Estimated available recycled aluminium from construction and buildings, by region



Source: Aluminium recyclability and recycling: towards sustainable cities, M Stacey & IAI, 2015, p222

---

36 Aluminium recyclability and recycling: towards sustainable cities, Michael Stacey and the International Aluminium Institute, 2015 (http://www.world-aluminium.org/media/filer_public/2016/10/03/tsc_report2_arr_72dpi_release_locked_1016.pdf)

37 Collection of Aluminium from Buildings in Europe: A Study by Delft University of Technology, EAA, UMJ Boin JA van Houwelingen (2004) - http://www.european-aluminium.eu/media/1628/collection-of-aluminium-from-buildings-in-europe.pdf

One trade flow captured only in this section is the import and export of Al alloy items including bars, rods, profiles, hollow profiles, wire, plates, sheets, strips, tubes and pipes (see Table 37). We allocated some of this import flow to semi-manufactures used as inputs to the Al alloy construction element manufacturing process (D.1.3) and some to E.1.4, the import of finished manufactured products. This allocation was determined by mass balance considerations.

There is both new and old scrap recycling associated with Al alloy construction elements, D.1.5 and G.1.2. Al alloy construction waste at EoL is typically in large sections, of high quality and relatively clean, making it an attractive input for secondary Al production. The EoL functional recycling derived here corresponds to approximately 40% of this material getting processed by remelters rather than refiners.

Table 6: Sources and calculations used to derive the downstream material flows of Mg's use in Al construction applications. Value assigned corresponds to Mg content

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in Al construction elements: sold production in the EU	2.6 MT of Al consumed in buildings in the EU in 2012.* Mg content of construction Al alloys = 0.8%, Table 39. Flow D.1.2 subtracted from total.	14.4 kT
D.1.2	Mg in Al construction elements: exports from the EU	Applied production split in Table 42, i.e. 24% construction and buildings, to the 3,344 kT of European Al manufacturing throughput exported from Europe, Table 41. Mg content as derived in Table 39, 0.8%.	6.4 kT
D.1.3	Mg in Al semi-manufacture imports in the EU for use in producing construction elements	Proportion, determined by mass balance, of the imports of Al alloy bars, rods, profiles and hollow profiles, wire, plates, sheets and strips, tubes and pipes into the EU, Table 37 captured here, and the rest in E.1.4.	3.0 kT
D.1.5	Mg in Al construction element manufacturing waste in the EU sent for reprocessing	1,711 kT of European Al manufacturing throughput sent for scrap processing, Table 41. 7% of this flow allocated to construction elements.* Mg content as derived in Table 39, 0.8%.	1.0 kT
D.1.6	Mg in Al construction element manufacture waste exports from the EU	HS 76020000. Total export from EU using this trade code in 2012 was 1,084 kT, Table 23. Subtracted construction, packaging and transport old scrap, which left 21% of this flow, which we assumed had a very low Mg content of 0.3%.*	0.7 kT
E.1.1	In-use accumulation of Mg in Al construction elements	Difference between the Mg in Al alloys used in new construction projects (2.6 MT Al in 2012) and that reaching EoL in 2012 (0.4 MT).*	15.1 kT
E.1.4	Mg in Al construction elements imported into the EU	Proportion, determined by mass balance, of the imports of Al alloy bars, rods, profiles and hollow profiles, wire, plates,	3.9 kT

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
		sheets and strips, tubes and pipes into the EU, Table 37 captured here, and the rest in D.1.3.	
F.1.1	Mg in EoL Al construction element exports from the EU	HS 7602000. Total export from EU using this trade code in 2012 was 1,084 kT, Table 23. 7% of this flow allocated to construction elements.**	0.6 kT
F.1.2	Mg in EoL Al construction elements imported into the EU	HS 76020000. Total import from EU using this trade code in 2012 was 321 kT, Table 22. 7% of this flow allocated to packaging.**	0.2 kT
F.1.3	Mg in Al construction elements sent directly for disposal at EoL	5% of aluminium from ELV construction and buildings in the EU is not collected.* Assume this is all sent for disposal.	0.1 kT
F.1.4	Mg in Al construction element EoL waste in the EU sent for reprocessing	4,372 kT of EoL Al from Europe sent for reprocessing in Europe, Table 41. 7% of this flow allocated to construction elements.** Mg content = 0.8%.	2.4 kT
G.1.2	Mg in secondary material from recycling EoL Al construction elements sent for use in the EU	2.4 kT of Mg from construction Al scrap processed at EoL in the EU in 2012 with 0.8% Mg content.* Subtract flows G.1.3 to G.1.5 to derive by mass balance.	0.6 kT
G.1.3	Mg in secondary material from recycling EoL Al construction elements exported from the EU	166 kT unwrought aluminium alloys in secondary form (excluding aluminium powders and flakes) exported from EU in 2012, Table 36. 7% of this flow allocated to construction elements.**	0.1 kT
G.1.4	Mg from EoL Al construction element reprocessing to non-functional recycling in the EU	Mg melt losses from Al construction element recycling end up in salt slag. Assumed that 75% of oxide residues from salt slag recycling are non-functionally recycled and 25% disposed of. Of that non-functionally recycled, the processing losses assumed to be 25%.	1.3 kT
G.1.5	Mg from EoL Al construction element reprocessing sent for disposal in the EU	Non-recycled oxide residues from salt slag recycling and losses from the non-functional recycling of oxide residues allocated to this disposal flow.	0.4 kT

** Aluminium recyclability and recycling: towards sustainable cities, Michael Stacey and the International Aluminium Institute, 2015 (http://www.world-aluminium.org/media/filer_public/2016/10/03/tsc_report2_arr_72dpi_release_locked_1016.pdf)*
*** 7% based on sources of Aluminium scrap figure in End-of-waste Criteria for Aluminium and Aluminium Alloy Scrap: Technical Proposals, JRC, 2010 (http://ftp.jrc.es/EURdoc/JRC58527.pdf)*

4.6.2 Discrepancies and uncertainties encountered in the sub-flow

As with most other flows there are uncertainties stemming from the need to estimate an average Mg content for the Al alloys and with allocating certain proportion of reported trade to this particular Al alloy application. In this flow, however, there are also major uncertainties associated with the EoL scrap processing stage.

World Aluminium's Global Aluminium Flow 2012 was a key source of information for this flow, as was the International Aluminium Institute's report *'Aluminium's recyclability and recycling for sustainable cities*'. However, these sources were only useful up to the EoL collection stage for Al alloy construction elements: they did not discuss the processing of the EoL Al alloy scrap, whether it is by refiners or remelters. In lieu of data or industry estimates we covered this stage of the flow using a blend of mass balance, allocating a proportion of Al scrap flows to construction, and assumptions used across for all EoL Al alloys in this study regarding salt slag processing.

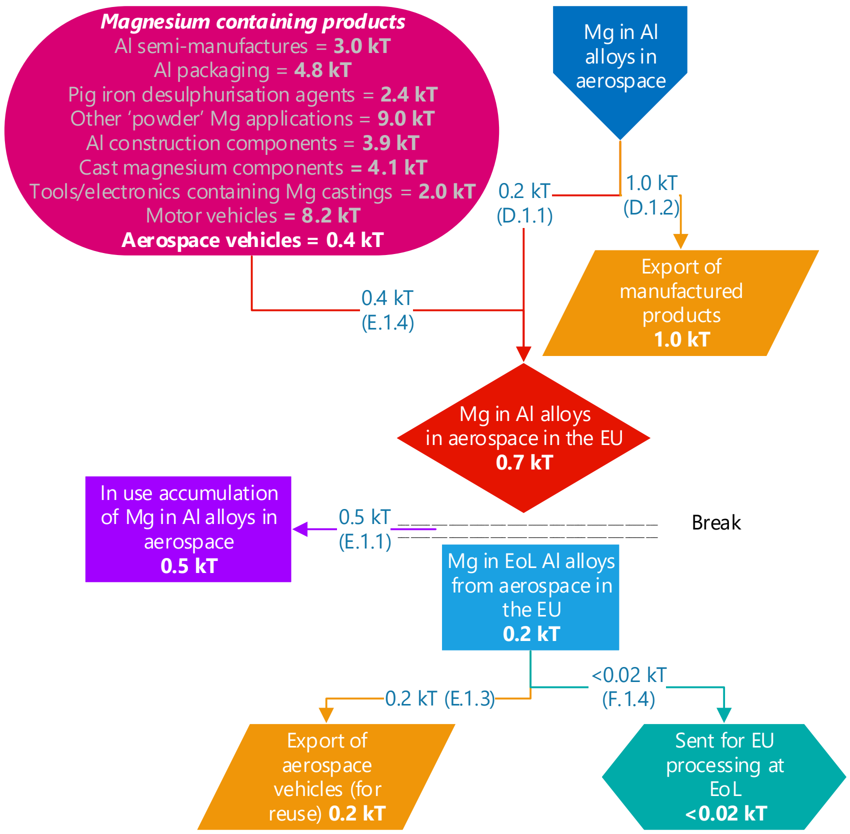
4.6.3 Key findings from the sub-flow

- Construction is the main Mg application for in-use accumulation, at ca.15 kT in 2012.
- Though Al construction elements have a high EoL collection rate, approximately 95%, there is much less EoL Al alloy coming out of demolished buildings than is going into new buildings.
- In terms of Mg consumption, construction elements account for 13% of the Mg in the EU. Of the Mg-containing products exported from the EU, Al construction components account for 16% of the total.

4.7 Mg in Al alloy aerospace applications: use and EoL situation

A map of the flows downstream of Mg's use in aerospace applications is shown in Figure 16. These flows are also depicted in the Sankey diagram in Figure 31. The sources and calculations used to derive each flow are listed in Table 7.

Figure 16: Map of downstream flows related to Mg's use in Al alloy aerospace applications



4.7.1 High level description of the sub-flow

Mg in aerospace applications is one of the smallest flows to be addressed. Though both Mg alloy and Al alloy components are used in aerospace applications, most of this Mg is in the Al alloys, which typically account for approximately 80% of a commercial aeroplane's weight. Whilst military aircraft tend to use less Al alloy than commercial aircraft, these alloys will typically be of the varieties containing more Mg, and military aircraft also contain more Mg alloy components.[38] Primarily because we had been unable to quantify the amount of Mg in Mg cast components used in aerospace applications, we compensated by assuming a high average Mg content of the Al alloys, i.e. 2.5% (see Table 40).

This average Mg content for Al alloys in aerospace applications and the widely-cited estimate that commercial aircraft are 80% Al by weight (though newer models, such as the Boeing 787 Dreamliner, contain less Al because of a switch to using more composites) were applied to all

[38] Chapter8: Aluminium alloys for aircraft structures from Introduction to Aerospace Materials by AP Mouritz, Elsevier, 2012

the flows in this section including the import and export of newly manufactured aircraft, D.1.2 and E.1.4. With the global air travel network doubling in size every 15 years approximately, according to the International Civil Aviation Organisation[39], some in-use accumulation of Mg is also expected in this flow. Our calculations suggest that approximately 70%, or 0.5 kT, more Mg was used in new aircraft in the EU in 2012 than was available from aircraft retired from the EU fleet in the same year.

Upon retirement, EU commercial aircraft are predominantly exported for re-use. They can be retro-fitted to change their function (e.g. passenger aircraft to cargo aircraft) and/or exported to developing countries where they may enjoy decades more years of use. Though there is some EU-based dismantling and recycling of aircraft, the scale of operations is very small, with only a handful of planes being processed per year. The recycling efficiencies at these operations, however, is expected to be high with a trial at Airbus - part funded by the EC - demonstrating that 85% of an aircraft's material weight can be recovered.[40]

Table 7: Sources and calculations used to derive the downstream material flows of Mg's use in Al alloy aerospace applications. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in aerospace applications: sold production in the EU	From own interpretation of Prodcom data, roughly 80% of aircraft produced in EU are exported (see D.1.2).	0.2 kT
D.1.2	Mg in aerospace applications: exports from the EU	HS 880200. Export from EU was 48,248 T in 2012, Table 29. Assume 80% Al by weight and 2.5% Mg content of Al alloy.	1.0 kT
E.1.1	In-use accumulation of Mg in aerospace applications	Difference between Mg production in new products and that in products reaching EoL in 2012.	0.5 kT
E.1.3	Export of Mg in aerospace vehicles for reuse	Large export market for old aircraft from Europe across Africa and Asia. Passenger aircraft also converted to carry cargo. Estimated 90% export for reuse.	0.2 kT
E.1.4	Mg in aerospace applications imported into the EU	HS 880200. Import from EU was 20,926 T in 2012, Table 28. Assume 80% Al by weight and 2.5% Mg content of Al alloy.	0.4 kT
F.1.4	Mg in aerospace applications at EoL sent for reprocessing in the EU.	Assume 10% of EoL aeroplanes not exported for reuse but instead dismantled and recycled in EU. This is 10% of an estimated 25 large commercial aeroplanes and 175 light aircraft retired in EU in 2012.*	<0.02 KT

** Estimate based on information from literature related to the part EC funded PAMELA project and 2011 article on EoL solutions: Retirement is not what it used to be (http://www.aels.nl/sites/aels/files/original/news/file/aircrafttechnologypas_special.pdf)*

[39] Global Air Navigation Capacity & Efficiency Plan: 013-2028 (https://www.icao.int/Meetings/anconf12/Documents/Draft%20Doc%209750.GANP.en.pdf)

[40] http://www.sustainableaviation.co.uk/wp-content/uploads/2015/09/SBAC-Aviation-and-Environment-Briefing-Paper-%E2%80%93-End-of-Aircraft-Life-Initiatives.pdf

4.7.2 Discrepancies and uncertainties encountered in the sub-flow

Because aircraft, by their very nature, are extremely mobile it was difficult to identify how many aircraft are truly based in the EU, how many of them reach their EoL in the EU, and of those how many are dismantled in the EU. As there was no official data available to answer these questions we relied heavily on estimates and assumptions. Nevertheless, an industry source with knowledge of the aerospace market thought the overall figures derived were broadly in line with their expectations.[41]

4.7.3 Key findings from the sub-flow

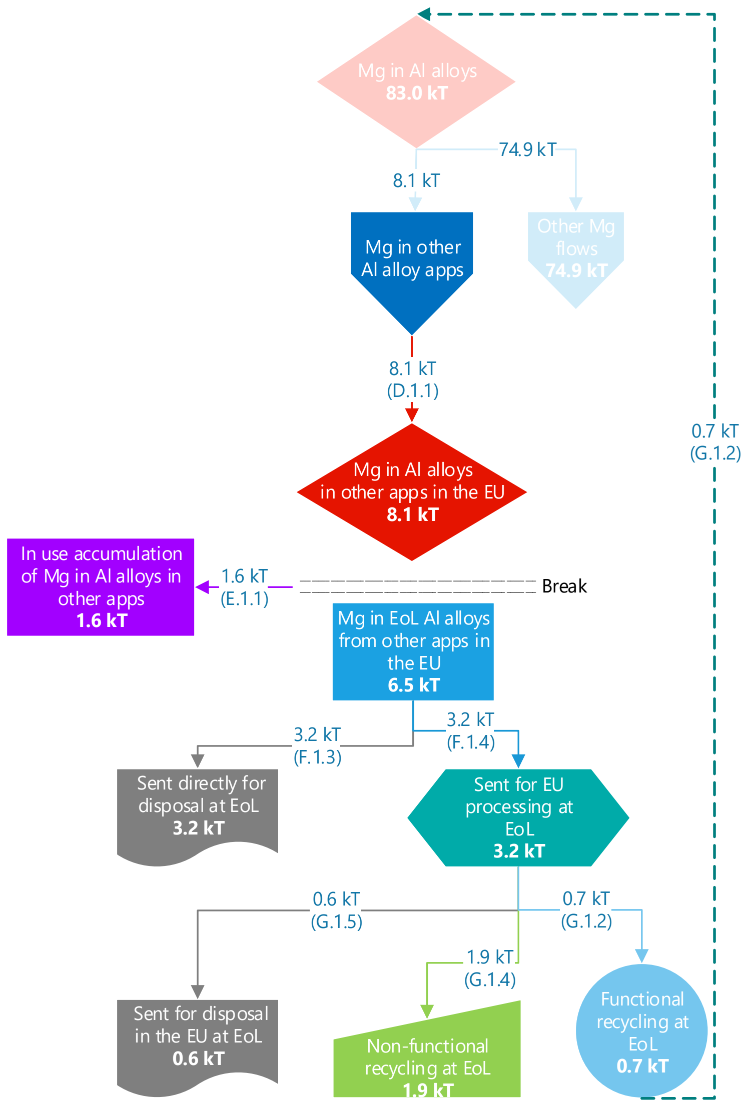
- Most of the Mg in aerospace applications is contained in Al alloys. Most of the Al alloys used in aircraft (2xxx and 7xxxx series) contain Mg (between 1 and 2.5 %).
- Mg is being accumulated in the world's growing fleet of aeroplanes.
- Most EU aeroplanes are exported, upon their retirement from the EU fleet, for use elsewhere in the world.
- Interest and activity in aeroplane dismantling and material recovery is increasing in the EU and elsewhere.

[41] Industry source 18

4.8 Mg in other Al alloy applications: use and EoL situation

Figure 17 shows a map of the flows downstream of Mg's use in 'other' Al alloy applications. These flows are also depicted in the Sankey diagram in Figure 31. The sources and calculations used to derive each flow are listed in Table 8.

Figure 17: Map of downstream flows related to Mg's use in 'other' Al alloy applications including marine, rail, consumer durables, equipment and machinery



4.8.1 *High level description of the sub-flow*

This is a catch-all flow to account for all the Mg in Al applications not captured in Sections 4.3, 4.5, 4.6 and 4.7. These are generally either small-scale applications of Al alloy or applications in which the alloys typically used contain no or very low levels of Mg. Because of their relatively low Mg content, these applications only account for 10% of the Mg in Al alloys used in the EU even though they make up 22% of the Al products manufactured in the EU.[42]

Table 8: Sources and calculations used to derive the downstream material flows of Mg's use in 'other' applications of Al alloy. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in 'other' Al alloy applications: sold production in the EU	Derived from mass balance, i.e. the difference between the Mg contained in Al alloys produced or imported into the EU and those used in vehicles, construction, aerospace and packaging. Equivalent to approx. 10% of Mg in Al alloy consumption. This is reasonable given that 22% of Al alloy applications are not captured by the above categories.	8.1 kT
E.1.1	In-use accumulation of Mg in 'other' Al alloy applications	Assumed 20% in-use accumulation of Mg in 'other' Al alloys applications.	1.6 kT
F.1.3	Mg in 'other' Al alloys sent directly for disposal at EoL	Estimated that half of 'other' Al alloys are directly disposed of at EoL. Consumer durables, equipment and machinery all expected to have high disposal rates.	3.2 kT
F.1.4	Mg in 'other' Al alloys element EoL waste in the EU sent for reprocessing	Remainder of 'other' Al alloys at EoL were assumed to be reprocessed in the EU. High recovery rates expected in some product categories, including marine and rail.	3.2 kT
G.1.2	Mg in secondary material from recycling EoL 'other' Al alloys sent for use in the EU		0.7 kT
G.1.4	Mg from EoL 'other' Al alloy reprocessing to non-functional recycling in the EU	Assumed that these' other' Al alloys are processed similarly to the dismantled Al components from vehicles at their EoL. This means 22% are recycled, 58% non-functionally recycled and 19% disposed of.	1.9 kT
G.1.5	Mg from EoL 'other' Al alloy reprocessing sent for disposal in the EU		0.6 kT

Given the wide variety of products that fell into this flow, including marine and rail applications, consumer durables, equipment and machinery, it was necessary to make some high-level assumptions about the in-use accumulation and EoL treatment. In lieu of better information we assumed that there are 20% fewer products available at EoL than being used in new products in 2012. This was lower than the 1/3 in-use accumulation assumed for non-

---

[42] Global Aluminium Flow 2012, World Aluminium

automotive applications of Mg castings (see Section 0). The allocation of a 20% in-use accumulation rate was based on an assumption that, for like-for-like products containing Mg castings versus Al equivalents, those containing Mg are generally of higher quality and thus durability.

At EoL we assumed that these 'other' Al alloys are processed similarly to the dismantled Al components from vehicles at their EoL, unless they were disposed of directly. This is a reasonable assumption given that the components recoverable from these 'other' applications are of a similar size or bigger (in the case of rail and marine) than those from vehicles.

4.8.2 Discrepancies and uncertainties encountered in the sub-flow

No import or export of products or wastes were identified for this Mg flow. This is likely to be a gross over-simplification. Ships, for example, are generally exported from the EU for breaking and material recovery, due to the attractive economics that countries with lower wages and lighter regulatory frameworks can offer. The EU is also a net exporter of rail parts, including rolling-stock: see Table 30 and Table 31.

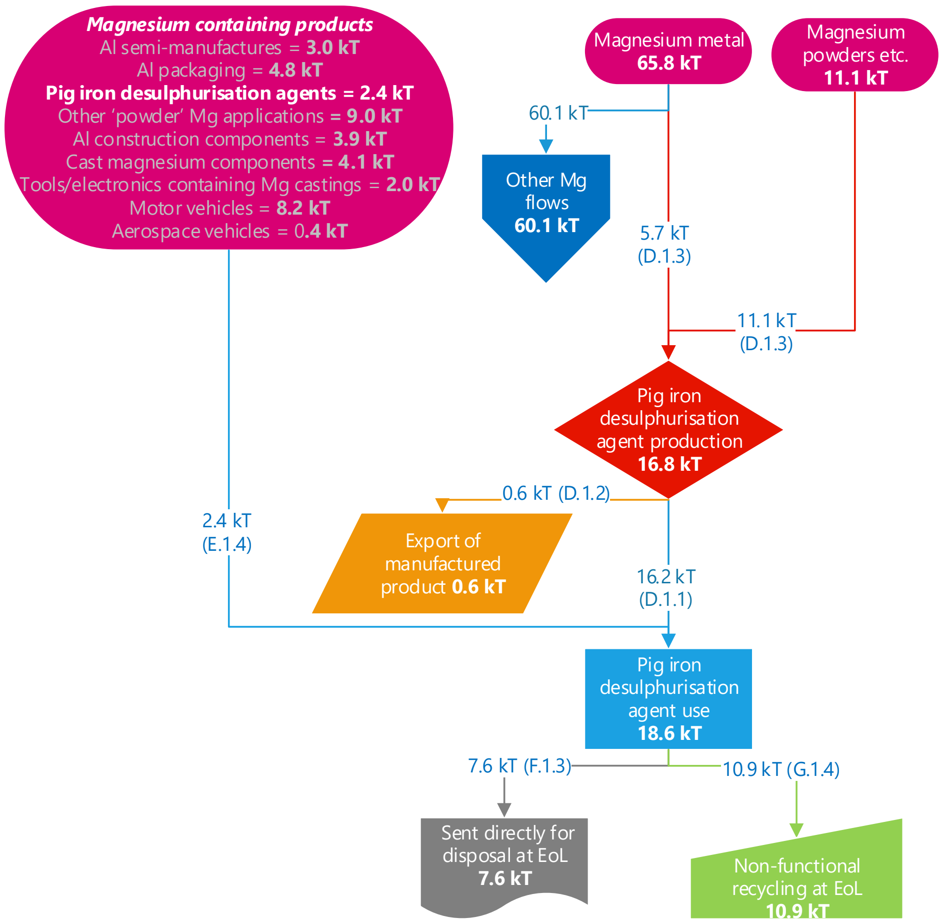
4.8.3 Key findings from the sub-flow

- These Al alloy applications have a low Mg content relative to those discussed in the preceding sections.
- Because of the large size of some of the applications covered in this flow, namely marine and rail, we assumed that there was considerable dismantling and alloy segregation at EoL, leading to a modest amount, 0.7 kT, of functional EoL Mg recycling.

4.9 Mg pig iron desulphurisation agents: production, use and EoL situation

Figure 18 maps the flows related to Mg's use in pig iron desulphurisation agents. These flows are also depicted in the Sankey diagram in Figure 32. The sources and calculations used to derive each flow are listed in Table 9.

Figure 18: Map of flows related to Mg's use in pig iron desulphurisation agents



4.9.1 *High level description of the sub-flow*

Mg metal in powdered or granulated form is added to molten pig iron to react with sulphur to form MgS (magnesium sulphide). MgS floats on the surface of the molten metal and can easily be skimmed off. Mg metal has a higher affinity to sulphur than other commonly used desulphurisation agents, namely lime and calcium carbonate, but is more expensive. Often Mg is co-injected into the pig iron along with one of the other desulphurisation agents which further increases its ability to remove sulphur. An industry source indicated that the ratio of Mg to other desulphurisation agents they use can be influenced by the price of Mg.[43]

We obtained various estimates from industry as to the overall consumption of Mg in pig iron desulphurisation agents in the EU. These estimates ranged from 15 to 70 kT and were either based on market knowledge or back-calculations based on the output of blast furnaces in the EU.[44] We also considered the split between Mg applications in Europe derived by Roskill in their 2012 market report on Mg.[45] The final value we derived for Mg in pig iron desulphurisation agent consumption in the EU in 2012 was 18.6 kT, which was near the bottom of the range of estimates we received but fitted well with the constraints on the system dictated by the finite amount of Mg imports into the EU.

Pig iron desulphurisation agents were reported by industry to be predominantly made from primary Mg metal. One EU-based producer mentioned that some of this primary material could potentially be substituted for by secondary material such as the turnings from Mg alloy foundries. However, they also cited that current regulations concerning the transboundary shipping of Mg turnings classified as waste effectively prohibited this practice in the EU. As such we have assumed all pig iron desulphurisation agents are produced from imported primary Mg metal or granules.

The MgS-containing skimmings removed from the ladles of molten iron are known as desulphurisation slags. The applications for desulphurisation slags can be like those of other slags, e.g. cement production, landfill construction and aggregates. There have also been trials of its use as a sulphur-rich soil conditioner.[46]

Table 9: Sources and calculations used to derive the downstream material flows of Mg's use in pig iron desulphurisation agents. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in pig iron desulphurisation agents: sold production in EU	D.1.2 subtracted from D.1.3	16.2 kT
D.1.2	Mg in pig iron desulphurisation agents: exports from EU of manufactured products	HS 81043000, Table 19. Assigned 60% of this trade flow here and the remainder to 'other' Mg powder applications. Split based on approx. application split.*	0.6 KT
D.1.3	Mg in Mg metal imports into EU for producing pig iron desulphurisation agents	Total (16.8 kT) based on triangulation of estimates from industry sources (1, 2, 4 and 18). Split between metal and powder/ granules/turnings imports determined by mass balance.	5.7 kT
D.1.3	Mg in Mg powder imports into EU for		11.1 kT

[43] Industry source 1

[44] Industry sources 1,2,3,4 and 18

[45] Application split used by IMA, from Roskill's report on magnesium metal: global industry markets and outlook (https://roskill.com/product/magnesium-metal-global-industry-markets-outlook/)

[46] Best Available Techniques (BAT) Reference Document for Iron and Steel Production, Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control), JRC, 2013. Figure 7.12

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
	producing pig iron desulphurisation agents		
E.1.4	Mg in pig iron desulphurisation agents imported into EU	5 kT of magnesium desulphurisation agents imported annually into the EU, CIS and Turkey, according to an industry source 4. Assuming 48% goes to the EU (based on share of crude steel production) this corresponds to 2.4 kT of imports in EU.	2.4 kT
F.1.3	Mg in slags from pig iron desulphurisation sent directly for disposal at EoL	41% of desulphurisation slag, containing the magnesium containing residues, is landfilled.**	7.6 kT
G.1.4	Mg in slags from pig iron desulphurisation non-functionally recycled in EU	37% of desulphurisation slag, containing the Mg residues, is recycled on-site with the remainder sold or used externally. We assume that all these non-landfill end-fates constitute functional recycling and the recycling efficiencies are 100%.**	10.9 kT

* *Application split used by IMA, from Roskill's report on magnesium metal: global industry markets and outlook (https://roskill.com/product/magnesium-metal-global-industry-markets-outlook/)*

*** Best Available Techniques (BAT) Reference Document for Iron and Steel Production, Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control), JRC, 2013. Figure 7.12*

4.9.2 Discrepancies and uncertainties encountered in the sub-flow

Because of the range of industry estimates received it was initially quite difficult to determine the overall size of this flow. More certainty was made possible by applying the constraints set by the amount of Mg imports into the EU, and comparing our findings to those in Roskill's market study.[47]

The fate of the desulphurisation slag was based on one literature source, with none of the industry sources able to comment with any certainty on this subject. Because none was provided, we assumed an efficiency for the non-functional recycling of 100%. We presume that the main reason for slag disposal instead of non-functional recycling here is the cost of transport, which may preclude the slag from being used in some off-site applications.

4.9.3 Key findings from the sub-flow

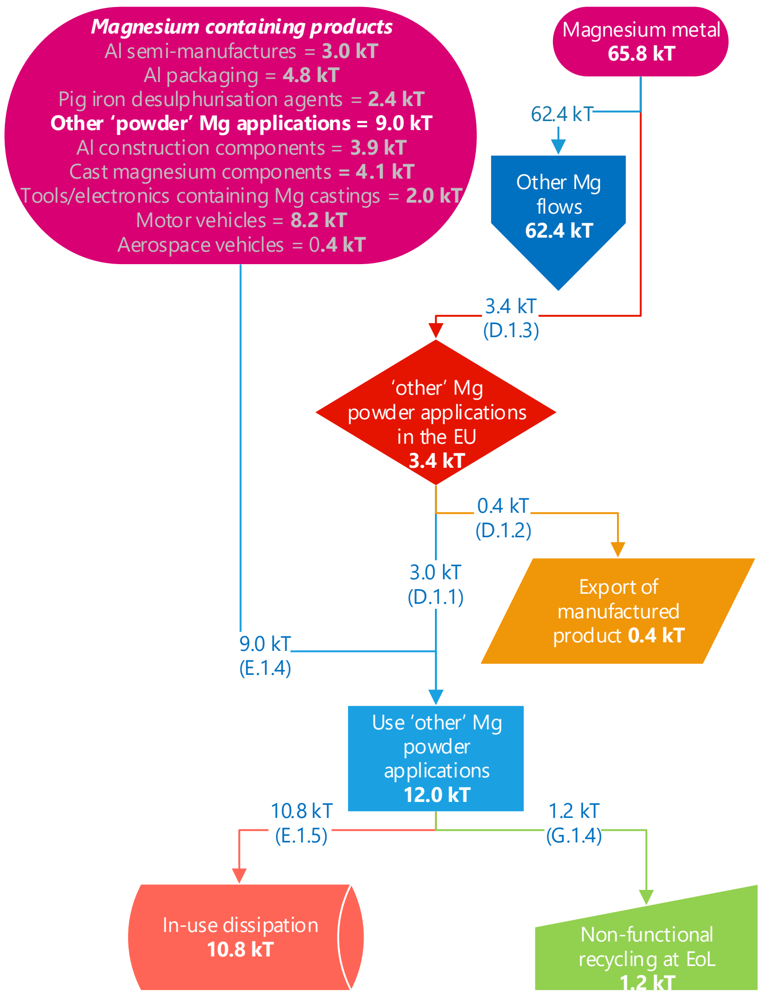
- Pig iron desulphurisation agents in the EU are produced from primary material.
- 90% of the pig iron desulphurisation agents used in the EU are produced in the EU.
- Mg's use in this application correlates to primary steel production but is also sensitive to the relative price of Mg to other desulphurisation agents.
- All the Mg ends up in desulphurisation slags that are skimmed off the surface of the molten iron and either disposed of (41%) or non-functionally recycled.

[47] *Magnesium metal: global industry markets and outlook* https://roskill.com/product/magnesium-metal-global-industry-markets-outlook/

4.10 Other Mg powder applications: production, use and EoL situation

Figure 19 maps the flows related to Mg's use in 'other' Mg powder applications. These flows are also depicted in the Sankey diagram in Figure 32. The sources and calculations used to derive each flow are listed in Table 10.

Figure 19: Map of flows related to Mg's use 'other' Mg powder applications including pyrotechnics, Grignard reagents and refractory materials



4.10.1 High level description of the sub-flow

This flow captures all applications of Mg powders, granules, flakes etc. excluding in pig iron desulphurisation agents. One industry source estimated that, in the EU, 70% of these 'other' Mg powder products are used as Grignard reagents, 20% are used in pyrotechnics and 10% in refractory materials.[48]

[48] Industry source 3

Based on mass balance consideration and the constraints set by the overall imports of Mg into the EU, 75% of these 'other' Mg powder-based products consumed in the EU were estimated to be imported in ready-for-use form rather than being manufactured in the EU.

We assumed that all the Mg in the Grignard reagents and pyrotechnic applications are dissipated in use. Only that used in refractory materials are non-functionally recycled at their EoL.

Table 10: Sources and calculations used to derive the downstream material flows of Mg's use in 'other' Mg powder applications. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.1	Mg in 'other' Mg powder applications: sold production in EU	D.1.2 subtracted from D.1.3	3.0 kT
D.1.2	Mg in 'other' Mg powder applications: exports from EU of manufactured products	HS 81043000, Table 19. Assigned 40% of this trade flow here, and the remainder to the pig iron desulphurisation agent flow. Split based on approx. application split.*	0.4 kT
D.1.3	Mg in Mg metal imports into EU for producing 'other' Mg powder products	Mass balance approach taken. Difference between the expected consumption in the EU*, and that imported as finished manufactured products (E.1.4)	3.4 kT
E.1.4	Mg in 'other' Mg powder products imported into EU	HS 81043000, Table 18. Assigned 40% of this trade flow here, and the remainder to the pig iron desulphurisation agent flows D.1.3 and E.1.4. Split based on approx. application split.*	9.0 kT
E.1.5	In-use dissipation of Mg during lifecycle of 'other' Mg powder products	Industry source 18 suggested that the Mg in refractory material is non-functionally recycled but that in Grignard reagents and pyrotechnics is dissipated in use; i.e. 10% non-functional recycling and 90% in-use dissipation. (Split supplied by industry source 3)	10.8 kT
G.1.4	Mg at EoL of 'other' Mg powder products non-functionally recycled in EU		1.2 kT

* *Application split used by IMA, from Roskill's report on magnesium metal: global industry markets and outlook (https://roskill.com/product/magnesium-metal-global-industry-markets-outlook/)*

4.10.2 Discrepancies and uncertainties encountered in the sub-flow

The same uncertainties associated with allocating various proportions of Mg import flows to the different Mg applications applies here. Because there was no EoL functional recycling expected in this flow, we could only make a cursory assessment of the EoL fate of the Mg in this flow.

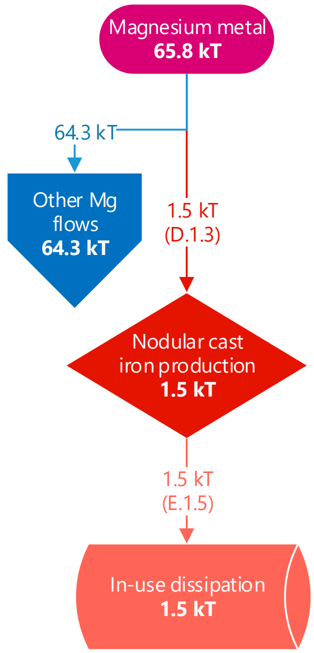
4.10.3 Key findings from the sub-flow

- This flow has the largest reliance of all on the import of Mg in ready-for-use products.
- 90% of the Mg in this flow is dissipated in use, leaving little opportunity for increasing Mg recovery.

4.11 Mg for nodular cast iron production: use and EoL situation

A map of the flows related to Mg's use in nodular cast iron is shown in Figure 20. These flows are also depicted in the Sankey diagram in Figure 32. The sources and calculations used to derive each flow are listed in Table 11.

Figure 20: Map of flows related to Mg's use in nodular cast iron



4.11.1 High level description of the sub-flow

This being the smallest Mg flow under consideration it was analysed in less detail, given it would have very little impact on the overall Mg material flow analysis.

Adding very small amounts of Mg (around 0.04%) to cast iron leads the graphite inclusions in the metal to become globular instead of in flakes. This reduces stress concentration in the metal and reduces its brittleness. Application of nodular cast iron[49] is in iron pipes, manhole covers and automotive passenger cars.

Imports exports of this product were not considered as we were unable to identify a Customs Code that only covered this specific material. Instead we relied on an industry estimate of the amount of Mg consumed in this application in the EU. Using an Mg concentration of 0.04%, and assuming zero processing losses, this corresponds to approximately 3,750 kT of nodular cast iron production in the EU.[50]

All Mg in this flow was assumed to effectively be dissipated in-use as at no stage in the product's use or EoL would the Mg be at a high enough concentration to enable its recovery.

---

[49] Nodular cast iron is also known as ductile cast iron or spheroidal graphite cast iron.

[50] This is in a similar range to that reported in http://www.globalcastingmagazine.com/wp-content/uploads/2013/08/CAEF_2012.pdf (4.5 MT) which includes Turkey but excludes some EU countries such as Poland and Denmark

Table 11: Sources and calculations used to derive the downstream material flows of Mg's use in nodular cast iron. Value assigned corresponds to Mg content.

Flow code	Description	Sources, calculations and assumptions used in deriving the flows	Value assigned
D.1.3	Mg in Mg metal imports into EU for producing nodular cast iron	Industry source 18 estimated the consumption of imported Mg metal in this application.	1.5 kT
E.1.5	In-use dissipation of Mg during lifecycle of nodular cast iron	At 0.04% Mg, no recovery of Mg from nodular cast iron is possible. Though not strictly dissipated in use as it is still inside the cast iron, it is effectively unavailable at EoL which is why it is included in this flow.	1.5 kT

4.11.2 Discrepancies and uncertainties encountered in the sub-flow

Very little detail because of extremely small size of flow.

4.11.3 Key findings from the sub-flow

- Nodular cast iron production in the EU consumed approximately 1.5 kT of Mg in 2012.
- As it is used in such low concentrations, all the Mg is effectively dissipated as soon as it is used in this application.

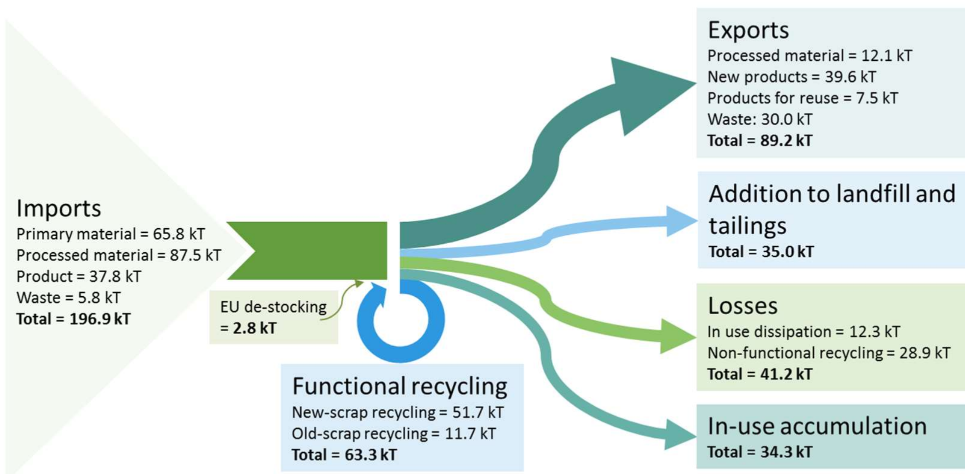
5 Overall material flow analysis

In this chapter, all the sub-flows covered in the Results chapter have been combined to produce aggregated flows of Mg into and out of the EU.

5.1 Simplified Sankey diagram

One important output of this exercise was a simplified Sankey diagram for Mg in the EU such as presented in the MSA report and reproduced in Figure 3. This simplified Sankey diagram, in which the width of the arrows roughly scale with the size of the flows, is shown in Figure 21. For a more accurate version see Figure 26 in Annex D.

Figure 21: Simplified Sankey diagram of Mg in the EU in 2012 based on this analysis



Some of the main differences between the numbers in Figure 21 and those in Figure 3 are:

- More imports by nearly 30 kT in new analysis.
  - The discrepancy is to be related to the import of primary and processed materials.
  - As imports were primarily based on trade data, data from World Aluminium's material flow analysis and some assumptions concerning Mg content of Mg and Al alloys, there is high confidence in the numbers derived in the new analysis.
- EU de-stocking flow added in new analysis.
  - Flow added to balance the inputs and outputs of the material flow analysis.
  - The year-on-year change in Mg alloy stocks in the EU of this order of magnitude is thought to be reasonable by industry experts.
- Functional recycling nearly 3x higher in new analysis.
  - Only EoL functional recycling was considered in MSA study, which was 2x higher than in the new analysis.
  - The new-scrap recycling shown here is predominantly contracted out remelting of Mg foundry waste. Not included here is about 9 kT of functional new-scrap recycling that the foundries carry out themselves.
  - The value for EoL scrap recycling in the new analysis might be lower than the MSA analysis because of cautiousness in allocating material to EoL functional recycling flows due to the large uncertainties in the collection rates and Mg recycling efficiencies of EoL Mg containing products.

- More exports by nearly 50 kT in new analysis.
  - As exports were primarily based on trade data, data from World Aluminium's material flow analysis and some assumptions concerning Mg content of Mg and Al alloys, there is high confidence in the numbers derived in the new analysis.
  - The nature of the waste exported from the EU is discussed further below.
- Addition to landfill and tailings reduced by 70% in new analysis
  - Material allocated to landfill in MSA study is primarily diverted to non-functional recycling and in-use accumulation.
  - The landfill rate (tonnes landfilled/tonnes imported) decreased from 68% in the MSA analysis to 18% in the new analysis.
- Subtraction to in-use stock changed to in-use accumulation in new analysis.
  - The discrepancy of over 40 kT is possibly partly because the MSA study used 'noisy' data on the year-by-year variation in production, especially of vehicles.
  - The MSA study apparently did not consider the sizeable accumulation of Mg in the Al alloys used in building and construction.

5.1.1 Focus on waste flows

The flow of Mg in waste material into and, particularly, out of the EU requires special attention to rule out, if possible within the scope of this study, the dumping of problematic waste streams in less-developed countries.

The import of 5.8 kT of Mg waste into the EU is captured in the trade codes covering Mg waste and scrap (Table 16) and Al waste and scrap (Table 22). For both these import flows, the EU's main trading partner is Switzerland.

Of the 30 kT of waste exported from the EU, half is associated with new Mg alloy scrap and half with old Al alloy scrap. Again, the export of this material is captured by trade codes for Mg waste and scrap (Table 17) and Al waste and scrap (Table 23). This time, however, the EU's main trade partners are the USA, Brazil and Canada for Mg scrap and China, India, Korea and Pakistan for Al scrap. Due to the US's anti-dumping tariffs on Mg from China, Mg sourced from elsewhere commands a premium in the USA. For this reason, it is not unreasonable to assume that some of the Mg scrap imported into Brazil and Canada might also be being processed to supply the US market.

Nearly 90% of the Al alloys exported from the EU originate from shredded ELVs, with the rest from dismantled ELV components and construction elements. Some of the waste exported to these (generally) lower-wage economies could be being hand-sorted, though the incidence of this practice is thought to be decreasing. Energy costs, local scrap availability, and waste disposal costs are other factors that affect the competitiveness of Al recyclers. The high cost of disposing responsibly of salt slags in the EU might be one reason that some of the Al scrap generated in the EU is being exported to lower-regulatory jurisdictions for recycling.[51]

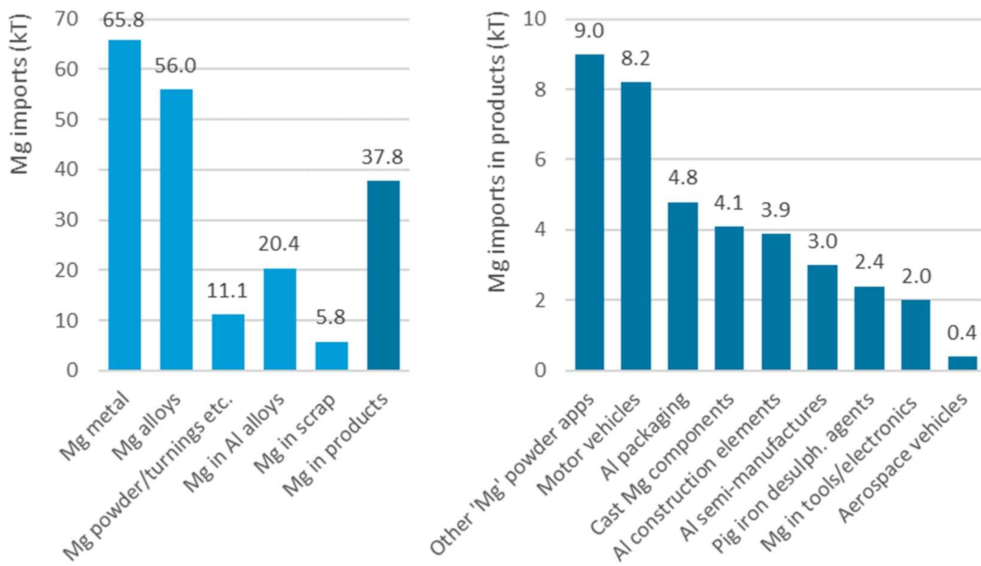
In conclusion, we believe that the clear majority of the Mg containing waste exported from the EU is being reprocessed. However, because of lower standards of salt slag recycling in some of the main countries receiving the Al alloy scrap, a higher proportion of the Mg contained might be ending up in landfill than it does in the EU.

[51] Aluminum Recycling, Second Edition, Edited by ME Schlesinger, CRC Press, Page 188

5.2 Profile of Mg imports into the EU

The EU is 100% reliant on the import of Mg, either as primary or processed materials or in finished products. For 2012 we identified that 196.9 kT of Mg was imported into the EU, one third of which was in the form of Mg metal and another third in the form of processed Mg materials (alloys and powders/turnings) (Figure 22).

Figure 22: Breakdown of the forms in which Mg is imported into the EU (Left); Split of the Mg containing products imported into the EU (Right)



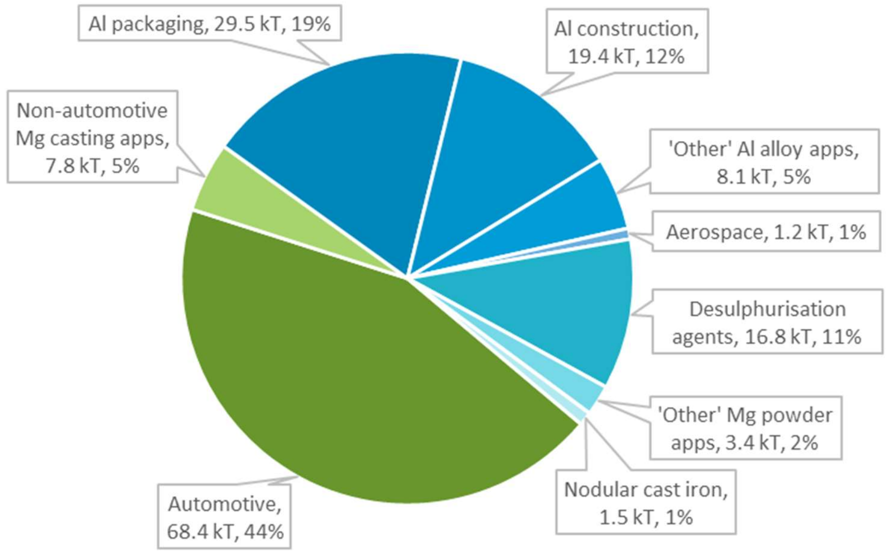
Note, however, that according to the trade data in Annex A, 9.5 kT of the Mg imported into the EU in primary or processed form is directly re-exported without being used in the EU. This includes 2.5 kT of Mg in Mg metal, 6.1 kT of Mg in Mg alloys, and 0.9 kT of Mg in Al alloys.

There is also a substantial amount of Mg imported into the EU in finished products (37.8 kT) and in Al alloys (20.4 kT). Of the imported Mg in products, approximately one third is in the form of powdered or granulated Mg, slightly more than one third is in Al alloys, and the remainder is in Mg cast components.

5.3 Profile of use of Mg in EU manufacturing

A total of 156.1 kT of Mg is used in the manufacturing of finished products in the EU, including those products ultimately exported from the EU. 44% of the Mg is used in motor vehicle manufacture, and 37% in Al alloy applications such as packaging and construction (Figure 23).

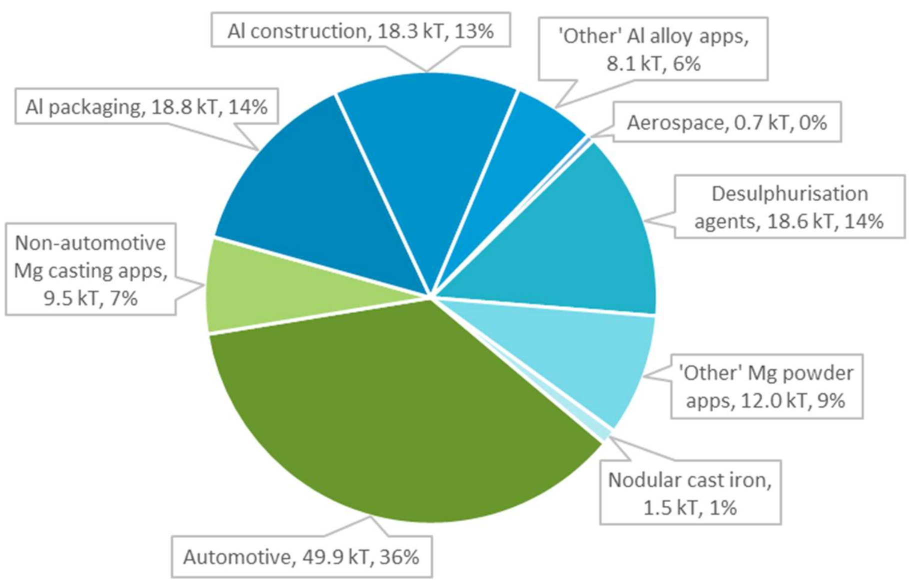
Figure 23: Use of Mg in EU manufacturing in 2012



5.4 Profile of EU consumption of Mg: in-use stage

Due to differences in the relative import/export of finished products containing Mg from the EU, as well as waste generation during the manufacturing stage, there is less Mg consumed in finished products (137.4 kT) in the EU than is consumed at the manufacturing stage. As shown in Figure 24, the breakdown of Mg consumption at the 'in-use' stage is quite different to at the manufacturing stage.

Figure 24: Consumption of Mg in the EU in 2012



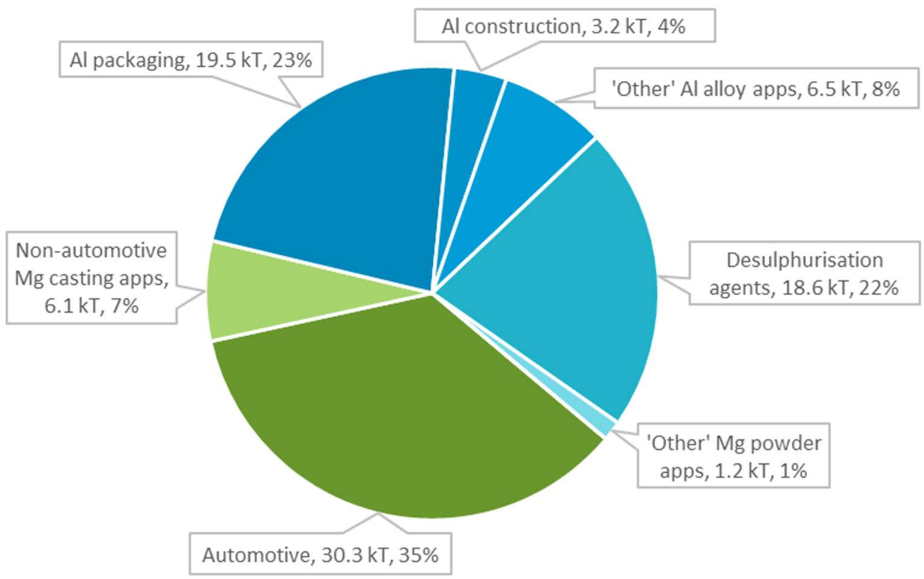
Firstly, there is 27% less Mg used in the vehicles used in the EU compared to those manufactured in the EU, because so many more cars are exported from the EU than imported into it. Waste generation and higher exports than imports also explain the 57%

difference in Mg in Al packaging applications between the manufacturing and in-use stages of the material flow analysis. Conversely, because of high levels of finished 'other' Mg powder product imports, there is 4x more Mg consumed in this application than manufactured in the EU.

5.5 Availability of EoL Mg

The amount of Mg available in EoL products in 2012 was also estimated. These figures do not reflect differences in the collection and processing efficiencies of the EoL products; simply the amount of Mg that they contain. Excluding products that are exported from the EU for reuse and those dissipated in use, there is 85.4 kT of Mg available in EoL products in the EU (Figure 25).

Figure 25: Availability of Mg in EoL products in the EU in 2012



Note: No Mg available from EoL aerospace applications (nearly all exported for reuse) or nodular cast iron (where all Mg is dissipated in use).

5.6 Derivation of the EoL-RIR

The End of Life - Recycling Input Rate (EoL-RIR) for Mg in the EU was also derived as part of this study:

$$\mathrm{EoL-RIR} = \frac{Input\ of\ 2ary\ material\ from\ old\ scrap\ to\ the\ EU}{Input\ of\ 1ary\ material\ to\ the\ EU + Input\ of\ all\ 2ary\ material\ to\ the\ EU}$$

$$= \frac{G.1.2}{C.1.3 + D.1.3 + C.1.4 + G.1.2} = \frac{11.7\ kT}{52.7\ kT + 105.2\ kT \quad 3.6\ kT \quad 11.7\ kT} = 7\%$$

Note: only non-zero flows included in this definition of EoL-RIR, i.e. flows G.1.1, B.1.1 and B.1.2 excluded.[52]

[52] Based on MSA methodology for deriving the EoL-RIR

The breakdown of these flows is as follows:

G.1.2 (Production of secondary material from post-consumer functional recycling (old scrap) in EU sent to manufacture in EU) - **11.7 kT**, of which: - 9.0 kT Al packaging - 1.4 kT automotive - 0.7 kT 'other' Al alloy applications - 0.6 kT Al construction elements
C.1.3 (Imports to EU of primary material used in the processing stage) - **52.7 kT**, of which: - 3.9 kT Mg metal for Mg alloy production - 5.6 kT Mg alloy miscategorised as Mg metal - 43.2 kT Mg metal used in Al alloy production (1ary +2ary)
D.1.3 (Imports to EU of processed material used in the manufacturing stage) - **105.2 kT**, of which: - 56.0 kT Mg alloy - 4.1 kT Mg cast components - 20.4 kT Al alloys - 3.1 kT Al construction semi-manufactures - 16.8 kT powder for desulphurisation agent production - 3.4 kT powder for 'Other' Mg powder applications - 1.5 kT Mg metal for nodular cast iron
C.1.4 (Imports to EU of secondary material input into the processing stage) - **3.6 kT**, of which: - 2.8 kT Mg scrap - 0.8 kT Al alloy scrap

The definitions of primary and processed material used here for deriving the EoL-RIR imports differ to those used in Figure 21 because here the imports are differentiated based on which stage of the material flow they are input into, i.e. primary material into the processing stage and processed material into the manufacturing stage. In reality, however, some primary material is used directly in the manufacturing stage; for example, Mg metal use in nodular cast iron production. Also, some articles that were classified as products in Figure 22 (e.g. Mg cast components and Al construction semi-manufactures) are classed here as processed materials as they are inputs into the manufacturing stage.

The EoL-RIR derived for Mg in the EU is low relative to the global (not just EU) EoL-RIR of Al which is approximately 12%. This value for Al is based on the information in the 2013 Global Mass Flow of Aluminium:[53]

$$\mathrm{EoL-RIR} = \frac{\textit{Recycled old scrap}}{1\textit{ary material input} + \textit{All scrap used in production}}$$

$$= \frac{14\ MT}{51\ MT + 62\ MT} = 12\%$$

[53] Aluminium recyclability and recycling: towards sustainable cities, Michael Stacey and the International Aluminium Institute, 2015 (http://www.world-aluminium.org/media/filer_public/2016/10/03/tsc_report2_arr_72dpi_release_locked_1016.pdf) - Page 41

6 Conclusions

Mg's strategic importance to the EU is guaranteed by its use in steel, aluminium alloy and (nodular) cast iron production: key industrial sectors. It also supports manufacturing in the EU, particularly in the automotive sector where light-weighting to achieve higher fuel efficiencies has become more important to regulatory bodies as well as to consumers. The 100% reliance on imports for primary Mg, mostly from China, also means it is considered a critical raw material by the EC. Nevertheless, despite its importance to the EU, the availability of literature and data on the EU Mg market was relatively thin. This was primarily, we assume, a result of the opaque nature of commodity markets, particularly small ones. We hope in this study to have, at the very least, illuminated somewhat the intricacies of the Mg flows in the EU.

The main outcome of this study is a fully transparent material flow analysis of Mg in the EU in which the derivation of every individual flow can be queried and potentially improved upon in future iterations of this type of work. This openness about the strengths and weaknesses of the data and estimates underlying the material flow analysis is important because, despite our best efforts and input from industry stakeholders, there were certain flows for which we had to rely on estimates, assumptions and proxy measures in lieu of more reliable data.

Nevertheless, we are confident that the overall material flow analysis produced is a significant improvement on that for Mg in the MSA study. We are most confident in the levels of imports and exports reported as these are based on official trade statistics. Production and recycling data availability varied across sub-flows, but was considerably strengthened by input from industry stakeholders, a source not exploited by those carrying out the MSA study. Where necessary, we also used mass balance considerations to allocate values to flows such that the flow of Mg into and out of various stages and in various sub-flows balanced. Within rounding errors, all stages in the sub-flows and overall Mg system balanced.

The material flow analysis presented here (see the simplified Sankey diagram in Figure 21) depicts a metal that is considerably more attractive to the circular economy than suggested by the MSA study. Whereas previously it was thought that 114 kT (or 67% of Mg imports) of Mg was landfilled in the EU in 2012, this study identified only 35 kT (or 18% of Mg imports). Based on the nature of the main trading partners, we can also postulate that the 30 kT of Mg exported from the EU as waste is predominantly diverted from landfill. However, to be more confident on this matter would require conducting a global material flow analysis of Mg.

Despite its modest EoL-RIR of 7%, there are opportunities to increase the EoL recycling of Mg. For example, technological advances in automated metal and alloy separation of ELV residues currently being investigated and commercialised mean that more Mg-containing ELV scrap could to be diverted to remelters instead of to refiners.[54] Though these technologies are primarily being investigated to improve the segregation of Al alloys and minimise the downgrading of wrought alloys to cast alloys during refining, it is expected that Mg recovery will also benefit. However, given the format and granularity of the ELV data available on Eurostat, Annex B, we anticipate that it will be difficult to monitor improvements in material recovery from ELVs.

[54] For example, in EU funded projects such as REALCAR2 and REALITY and SHREDDERSORT

Annex A *Trade data*

Table 12: Imports into the EU-28 in 2012 of 'Magnesium unwrought > 99.8% pure'

Trade partners	Volume traded (tonnes)	% of trade flow
China	61,689	94%
Russian Federation	2,850	4%
Israel	940	1%
Other	360	1%
Total	**65,839**	

Source: HS 810411

Table 13: Exports out of the EU-28 in 2012 of 'Magnesium unwrought > 99.8% pure'

Trade partners	Volume traded (tonnes)	% of trade flow
Norway	883	35%
USA	467	19%
Turkey	448	18%
Switzerland	342	14%
Serbia	104	4%
Iceland	65	3%
Other	185	7%
Total	**2,493**	

Source: HS 810411

Table 14: Imports into the EU-28 in 2012 of 'Magnesium unwrought nes' which we have interpreted as Magnesium alloys

Trade partners	Volume traded (tonnes)	% of trade flow
China	53,754	89%
Israel	4,754	8%
Serbia	1,380	2%
Other	303	1%
Total	**60,190**	

Source: HS 810419
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 15: Exports out of the EU-28 in 2012 of 'Magnesium unwrought nes' which we have interpreted as Magnesium alloys

Trade partners	Volume traded (tonnes)	% of trade flow
USA	2,075	32%
Switzerland	1,889	29%
Brazil	1,099	17%
Serbia	773	12%
Mexico	430	7%
Other	264	4%
Total	**6,530**	

Source: HS 810419
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 16: Imports into the EU-28 in 2012 of 'Magnesium waste and scrap'

Trade partners	Volume traded (tonnes)	% of trade flow
Switzerland	1,985	66%
USA	270	9%
Nigeria	215	7%
Mexico	104	3%
South Africa	103	3%
Rep. of Korea	95	3%
Other	240	8%
Total	**3,012**	

Source: HS 810420
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content. Given that this scrap originates in Mg alloy production (1ary and 2ary) as well as Mg casting, we assume that the Mg content of this trade flow is 93%.

Table 17: Exports out of the EU-28 in 2012 of 'Magnesium waste and scrap'

Trade partners	Volume traded (tonnes)	% of trade flow
USA	5,737	48%
Brazil	2,791	23%
Canada	2,085	17%
Ukraine	1,254	10%
Other	90	1%
Total	**11,957**	

Source: HS 810420
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content. Given that this scrap originates in Mg alloy production (1ary and 2ary) as well as Mg casting, we assume that the Mg content of this trade flow is 93%.

Table 18: Imports into the EU-28 in 2012 of 'Magnesium raspings/turnings/etc, size graded, powder'

Trade partners	Volume traded (tonnes)	% of trade flow
China	20,797	90%
USA	609	3%
Turkey	605	3%
Other	538	2%
Total	**22,549**	

Source: HS 810430

Table 19: Exports out of the EU-28 in 2012 of 'Magnesium raspings/turnings/etc, size graded, powder'

Trade partners	Volume traded (tonnes)	% of trade flow
Serbia	378	35%
Turkey	293	27%
South Africa	165	15%
USA	69	6%
Ukraine	40	4%
Brazil	38	4%
Other	92	9%
Total	**1,075**	

Source: HS 810430

Table 20: Imports into the EU-28 in 2012 of 'Magnesium, articles thereof nes'

Trade partners	Volume traded (tonnes)	% of trade flow
China	3,437	77%
USA	707	16%
India	122	3%
Switzerland	81	2%
Serbia	31	1%
Other	65	1%
Total	**4,442**	

Source: HS 810490
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 21: Exports out of the EU-28 in 2012 of 'Magnesium, articles thereof nes'

Trade partners	Volume traded (tonnes)	% of trade flow
Serbia	794	37%
Saudi Arabia	594	28%
Turkey	156	7%
Israel	83	4%
USA	72	3%
Switzerland	64	3%
Canada	60	3%
Other	318	15%
Total	**2,141**	

Source: HS 810490
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 22: Imports into the EU-28 in 2012 of 'Waste and scrap, aluminium'

Trade partners	Volume traded (tonnes)	% of trade flow
Switzerland	113,014	35%
Norway	28,666	9%
Saudi Arabia	16,089	5%
China	12,622	4%
Serbia	12,471	4%
United Arab Emirates	12,431	4%
Israel	11,672	4%
Iceland	9,445	3%
Russian Federation	9,063	3%
Cuba	8,041	3%
Other	87,856	27%
Total	**321,370**	

Source: HS 760200
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 23: Exports out of the EU-28 in 2012 of 'Waste and scrap, aluminium'

Trade partners	Volume traded (tonnes)	% of trade flow
China	498,552	46%
India	251,757	23%
Rep. of Korea	74,167	7%
Pakistan	66,410	6%

Switzerland	42,106	4%
Norway	31,897	3%
Other Asia, nes	26,201	2%
Thailand	21,106	2%
USA	17,612	2%
Other	53,904	5%
Total	**1,083,713**	

Source: HS 760200
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 24: Imports into the EU-28 in 2012 of 'Mowers, powered, lawn, with horizontal cutting device'

Trade partners	Volume traded (tonnes)	% of trade flow
China	59,175	58%
USA	38,794	38%
Japan	3,714	4%
Other	968	1%
Total	**102,651 (4,076,451 units)**	

Source: HS 843311
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 25: Exports out of the EU-28 in 2012 of 'Mowers, powered, lawn, with horizontal cutting device'

Trade partners	Volume traded (tonnes)	% of trade flow
Norway	3,241	22%
Switzerland	2,602	18%
Russian Federation	2,218	15%
Turkey	889	6%
USA	665	5%
Ukraine	562	4%
Australia	548	4%
Serbia	347	2%
Other	3,564	24%
Total	**14,635 (586,579 units)**	

Source: HS 843311
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 26: Imports into the EU-28 in 2012 of 'Chain saws'

Trade partners	Volume traded (tonnes)	% of trade flow
China	10,800	77%
USA	2,698	19%
Japan	510	4%
Other	32	0.2%
Total	**14,040 (2,241,310 units)**	

Source: HS 846781
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 27: Exports out of the EU-28 in 2012 of 'Chain saws'

Trade partners	Volume traded (tonnes)	% of trade flow
Russia	550	19%
USA	407	14%
Norway	229	8%
Turkey	156	5%
China	131	4%
Canada	123	4%
Peru	115	4%
Mexico	110	4%
Vietnam	104	4%
Other	1,014	34%
Total	**2,938 (433,816 units)**	

Source: HS 846781
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 28: Imports into the EU-28 in 2012 of 'Aircraft, spacecraft, satellites'

Trade partners	Volume traded (tonnes)	% of trade flow
USA	8,984	43%
Areas, nes	5,198	25%
Other Europe, nes	2,117	10%
Brazil	1,034	5%
Canada	736	4%
China	601	3%
Other	2,256	11%
Total	**20,926**	

Source: HS 880200
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 29: Exports out of the EU-28 in 2012 of 'Aircraft, spacecraft, satellites'

Trade partners	Volume traded (tonnes)	% of trade flow
USA	8,542	18%
China	8,095	17%
United Arab Emirates	3,538	7%
Malaysia	2,750	6%
Areas, nes	2,594	5%
Russian Federation	2,130	4%
Singapore	1,912	4%
Thailand	1,812	4%
Turkey	1,239	3%
Other	15,636	32%
Total	**48,248**	

Source: HS 880200
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 30: Imports into the EU-28 in 2012 of 'Parts of railway, tramway locomotives, rolling-stock'

Trade partners	Volume traded (tonnes)	% of trade flow
Ukraine	24,646	25%
Russian Federation	19,379	20%
China	17,383	18%
Switzerland	16,700	17%
Serbia	7,088	7%
USA	2,227	2%
Japan	2,150	2%
Turkey	1,927	2%
Other	7,030	7%
Total	**98,530**	

Source: HS 860700
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Table 31: Exports out of the EU-28 in 2012 of 'Parts of railway, tramway locomotives, rolling-stock'

Trade partners	Volume traded (tonnes)	% of trade flow
China	48,556	25%
Switzerland	29,565	15%
Ukraine	25,486	13%
USA	15,673	8%
India	9,842	5%
Russian Federation	6,840	3%
Serbia	6,012	3%
Turkey	5,738	3%
Other	48,616	25%
Total	**196,329**	

Source: HS 860700
Note: This is a record of the total volume of imports recorded under this trade code and not the Mg content.

Annex B *Waste data*

Table 32: ELV vehicle data: Total weight of vehicles exported in 2012 (tonnes)

Member state	Waste generated	Disposal	Recovery	Of which: recycling
Belgium	32,189	3,763	28,426	27,725
Bulgaria	0	0	0	0
Czech Republic	:	:	:	:
Denmark	0	0	0	0
Germany	27,437	3,474	23,963	22,325
Estonia	3,484	495	2,989	2,835
Ireland	:	:	:	:
Greece	:	:	:	:
Spain	0	0	0	0
France	135,430	17,958	117,472	112,013
Croatia	31,879	1	31,878	31,005
Italy	23,672	1,241	22,431	20,857
Cyprus	7,197	1,041	6,156	6,156
Latvia	275	18	257	257
Lithuania	15,545	:	15,545	15,545
Luxembourg	2,641	139	2,502	2,224
Hungary	254	10	244	242
Malta	1,851	0	1,851	1,847
Netherlands	27,949	2,396	25,553	22,841
Austria	0	0	0	0
Poland	3,391	0	3,391	3,391
Portugal	7,298	0	7,298	7,298
Romania	:	:	:	:
Slovenia	0	0	0	0
Slovakia	28	0	28	28
Finland	:	:	:	:
Sweden	0	0	0	0
United Kingdom	:	:	:	:
Sum	**320,520**	**30,536**	**289,984**	**276,589**

Source: Eurostat

Table 33: ELV vehicle data: Total weight of metal components (LoW: 160117+160118) processed in the EU in 2012 (tonnes)

Member state	Disposal	Reuse	Recycling
Belgium	0	0	5,381
Bulgaria			
Czech Republic			
Denmark			
Germany	444	19,548	33,269
Estonia	0	937	2,231
Ireland			
Greece			
Spain	0	65,143	40,923
France			50,157
Croatia	0	0	1
Italy			
Cyprus			25
Latvia	0	305	3,142
Lithuania			
Luxembourg			
Hungary			
Malta	0	4	0
Netherlands			
Austria	0	2,920	2,061
Poland			
Portugal	0	0	0
Romania			
Slovenia	0	7	2,050
Slovakia	0	156	2,595
Finland	0	0	0
Sweden			
United Kingdom			
Sum	**444**	**89,020**	**141,835**

Source: Eurostat

Table 34: ELV vehicle data: Total weight of non-ferrous materials (aluminium, copper, zinc, lead, etc.) from shredding processed in the EU in 2012 (tonnes)

Member state	Disposal	Incineration	Recycling
Belgium	166	52	6,902
Bulgaria	0	0	686
Czech Republic	0	0	115
Denmark	0	0	13,163
Germany	0	0	37,507
Estonia	0	0	233
Ireland			
Greece			
Spain	0	0	19,856
France	23	0	22,633
Croatia	0	0	0
Italy	0	0	10,591
Cyprus	0	0	340
Latvia	0	0	488
Lithuania			
Luxembourg	0	0	0
Hungary	0	0	41
Malta			
Netherlands	0	0	302
Austria	0	0	2,168
Poland	0	0	1,445
Portugal	0	0	1,588
Romania			
Slovenia	21	0	27
Slovakia	0	0	890
Finland	0	0	4,889
Sweden			
United Kingdom			67,875
Sum	**210**	**52**	**191,739**

Source: Eurostat

Annex C *Other supporting information*

Table 35: Typical Mg content of some of the most common Mg alloys and derivation of an average Mg content

Mg alloy name	Approximate Mg content
AZ91	91%
AM60	94%
AM50	95%
Weighted average	**93%**

Source: NADCA product specification standards for die castings / 2009[55]

Table 36: Production, imports and exports of 'Unwrought aluminium alloys in primary form (excluding aluminium powders and flakes)' into the EU-28 between 2012 and 2015

Trade partners	2012 (kT)		2013 (kT)	2014 (kT)	2015 (kT)
	primary	*secondary*			
Production	2,391	4,000	5,611	6,805	7,109
Imports	2,232	109	2,420	2,514	2,482
Exports	51	166	179	217	248
Apparent consumption	**4,573**	**3,943**	**7,852**	**9,102**	**9,343**

Source: PRC 24421153/4/5
Note: These values correspond to total Al alloy, not the Mg content

Table 37: Production, imports and exports of 'Aluminium alloy items' into the EU-28 between 2012 and 2015

PRC code	Description	Production (kT)	Imports (kT)	Exports (kT)	Apparent consumption (kT)
24422250	Aluminium alloy bars, rods, profiles and hollow profiles*	2,513	299	168	2,644
24422350	Aluminium alloy wire**	106	19	36	89
24422450	Aluminium alloy plates, sheets and strips >0,2 mm thick	3,515	519	609	3,425
24422650	Aluminium alloy tubes and pipes	132	36	23	144
	Sum	**6,267**	**873**	**837**	**6,303**

Source: PRC 24422-250/350/450/650
Note: These values correspond to total Al alloy, not the Mg content
** excluding rods and profiles prepared for use in structures;*
*** excluding insulated electric wire and cable, twine and cordage reinforced with aluminium wire, stranded wire and cables;*
† excluding hollow profiles, tubes or pipe fittings, flexible tubing, tubes and pipes prepared for use in structures, machinery or vehicle parts, or the like

[55] http://www.tcdcinc.com/media/2009_NADCA_Alloy_Data.pdf

Table 38: Derivation of typical Mg content of Al packaging

Product	Alloys	Mg content	Overall Mg content	Production in Europe (kT)†
Beverage can	3004 (body, 83%)*	1.05%	1.6%	1,261
	5182 (ends, 17%)*	4.5%		
Foil, aerosol cans,	1000, 3000 and 8000 series	0.05%-1.0%	0.5%	975
		Weighted average	**1.1%**	

*Sources: *Aluminum Recycling, Second Edition, Mark E. Schlesinger, CRC Press, 2013 (Page 23).*
†Global Aluminium Flow Model 2012, World Aluminium

Table 39: Derivation of typical Mg content of Al construction elements

Construction application	Alloys	Properties	Mg content	Weighting
Cladding systems	3103	Good strength and corrosion resistance	0.3 %	12
Chemical plants & road tankers	5083	Suitable for welding	4.45%	1
	5454		2.7%	1
Extruded window frames and roof trusses	6063	Lightness, strength and corrosion resistance	0.675%	2
	6061		1%	2
	6082		0.9%	2
		Weighted average	**0.8%**	

Sources: International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys (http://www.aluminum.org/sites/default/files/TEAL_1_OL_2015.pdf). Sustainable Aluminium Systems,,E Efthymiou, ÖN Cöcen and SR Ermolli, Sustainability 2010, 2, 3100-3109; For weightings assumed that there was twice as much Al used in cladding (3xxx series) than other regular construction applications (6xxx series) and that Al use in specialist industrial construction applications (5xxx series) is 1/3 of that in regular construction applications.

Table 40: Typical Mg content of some Al alloys used in aerospace applications

Aerospace application	Alloys	Properties	Mg content
Aircraft skins, cowls, aircraft structures	2024	High strength alloy with excellent fatigue resistance	1.5%
Cowls and baffle plating	3003	Corrosion resistance and workability	0%
Fuel tanks	5052	Corrosion resistance and workability, highest strength of non-treatable alloys	1.5%
Aircraft landing mats	6061	Good formability, heat-treatable and good corrosion resistance	1.0%
Use to strengthen aircraft structures	7075	Excellent strength-to-weight ratio	2.5%

Sources: History of Aluminium in the aerospace industry (https://www.metalsupermarkets.com/history-of-aluminum-in-the-aerospace-industry/); Aircraft materials, processes, and hardware Chapter 5 (https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_handbook/media/FAA-8083-30_Ch05.pdf)

Table 41: Flows of Al between Europe and the rest of the world (RoW) in 2012

Stage	Flow description	Value
Production in Europe (ingots)	Input from European scrap recovery	3,818 kT
	Input from European refining	1,784 kT
	Input from RoW	2,122 kT
	Production in Europe (1ary)	4,267 kT
	Production in Europe (2ary)	4,085 kT
Fabrication in Europe (semis)	Input from European production	7,649 kT
	Input from production in RoW	3,789 kT
	Fabrication in Europe	11,761 kT
Manufacturing in Europe (products)	Input from European fabrication	10,886 kT
	Input from fabrication in RoW	842 kT
	Manufacturing in Europe	11,728 kT
Use in Europe	Input from European manufacturing	6,673 kT
	Input from manufacturing in RoW	2,310 kT
	Use in Europe	8,984 kT
Scrap recovery in Europe	Input from European manufacturing	1,711 kT
	Input from EoL products	4,012 kT
	Scrap recovery in Europe	5,722 kT
Disposal and incineration in Europe		869 kT
Residue management in Europe		376 kT

Source: Global Aluminium Flow 2012, World Aluminium[56]
Note: These values correspond to total volume of material, not the Mg content

Table 42: Production of Al products in Europe

Mg alloy name	Product net shipments, Western Europe (kT)	% of net shipments	Average Mg content of Al alloys in this application
Buildings & construction	2,692	23%	0.8%
Transport - Automotive & light trucks	2,863	24%	1.0%
Transport - Aerospace	98	1%	2.0%
Transport - truck/ bus/ trailer/ rail/ marine/ other	1,299	11%	1.0%
Packaging - cans	1,261	11%	1.6%
Packaging - other (foil)	975	8%	0.5%
Machinery & equipment	699	6%	1.0%
Electrical - cable	474	4%	0.1%
Electrical - other	487	4%	0.1%
Consumer durables	353	3%	0.5%
Other (excl destructive uses)	209	2%	0.5%
Destructive uses	319	3%	0.5%
Total	**11,728**	**Weighted Average**	**0.9%**

[56] http://www.world-aluminium.org/statistics/massflow/

Source: Global mass flow model, 2014-2015 release, World Aluminium

Table 43: Sources of Al scrap

Source	Share of Al scrap
Transportation facility and vehicles	44%
Packaging	28%
Cable, wire, EEE and others	21%
Construction and building	7%

Source: End-of-waste Criteria for Aluminium and Aluminium Alloy Scrap: Technical Proposals, JRC, 2010 (http://ftp.jrc.es/EURdoc/JRC58527.pdf)

Table 44: Mg content of some common Al alloys as well as their main applications

Al alloy	% Mg	Main applications
3004	1.05	Sheet metal work, storage tanks, agricultural applications, building products, containers, electronics, furniture, kitchen equipment, and beverage can bodies.
5005	0.8	Specified for applications requiring anodizing including appliances, utensils, architectural and applications requiring good electrical conductivity.
5052	2	Stronger than 3003 yet readily formable in the intermediate tempers. Used in pressure vessels, fan blades, tanks, electronic panels, electronic chassis, medium strength sheet and marine applications, amongst others.
5083	4.45	Good corrosion resistance. For all types of welded assemblies, marine components, and tanks requiring high weld efficiency and maximum joint strength, such as cryogenic applications bridges, freight cars and drilling rigs.
5182	4.5	Beverage can lids/ends, relevant to the Al packaging flow captured in this study.
6061	1	Good general purpose alloy used for a broad range of structural applications and welded assemblies including truck components, railroad cars, pipelines, marine applications, furniture, agricultural applications, aircrafts, architectural applications and automotive parts amongst others.
6063	0.675	Used in pipe railing, furniture, architectural extrusions, appliance parts and trim, automotive parts, building products, electrical and electronic parts and highway signs amongst others

Source: Aluminium and Aluminium Alloys from Alloying: Understanding the Basics, J.R. Davis, p351-416[57]

Table 45: Derivation of average amount of Mg in Al alloys used in vehicles produced in 2012

Type of Al	Cast	Extruded	Forged	Rolled		Totals
Typical Al alloy	A356	AA6082	AA6082	AA5182 (23%)	AA6016 (77%)	
Average kg Al/vehicle	102.2 kg	14.0 kg	4.2 kg	18.2 kg		140 kg

57 https://materialsdata.nist.gov/dspace/xmlui/bitstream/handle/11115/173/Aluminum%20and%20Aluminum%20Alloys%20Davis.pdf?sequence=3

Max Mg content of alloy	0.45%	1.20%	1.20%	5.00%	0.60%	
Min Mg content of alloy	0.30%	0.60%	0.60%	4.00%	0.25%	
Max Mg content/ vehicle	0.46 kg	0.17 kg	0.05 kg	0.91 kg	0.11 kg	1.7 kg
Min Mg content/ vehicle	0.31 kg	0.08 kg	0.03 kg	0.73 kg	0.05 kg	1.19 kg
Average Mg content in the Al in a vehicle produced in 2012 =						**1.44 kg**

Sources: EAA Aluminium penetration in cars, Final Report, March 13, 2012 (Public version) by Ducker worldwide and Aluminium content in cars, Summary Report, June 2016 (Public version) by Ducker worldwide

Table 46: Derivation of average amount of Mg in Al alloys used in vehicles produced in 2002, i.e. those typically reaching their EoL in 2012

Type of Al	Cast	Extruded	Forged	Rolled		Totals
Typical Al alloy	A356	AA6082	AA6082	AA5182 (23%)	AA6016 (77%)	
Average kg Al/vehicle	92.8 kg	11.6 kg	2.3 kg	9.3 kg		116 kg*
Max Mg content of alloy	0.45%	1.20%	1.20%	5.00%	0.60%	
Min Mg content of alloy	0.30%	0.60%	0.60%	4.00%	0.25%	
Max Mg content/ vehicle	0.42 kg	0.14 kg	0.03 kg	0.46 kg	0.06 kg	1.1 kg
Min Mg content/ vehicle	0.30 kg	0.07 kg	0.01 kg	0.37 kg	0.02 kg	0.76 kg
Average Mg content in the Al in a vehicle produced in 2002 =						**0.93 kg**

Sources: EAA Aluminium penetration in cars, Final Report, 13 March 2012 (Public version) by Ducker worldwide and Aluminium content in cars, Summary Report, June 2016 (Public version) by Ducker worldwide
** Based on extrapolation of figures in the report.*

Table 47: Summary of Mg content in vehicles produced in 2002 and 2012

	2002	2012
Mg in Al alloys	0.93 kg	1.44 kg
Mg in Mg cast components*	2.2 kg	2.7 kg
Total	**3.1 kg**	**4.1 kg**

** Upper limit on Mg in automotive cast components in 2012 set by Mg casting production in the EU and the imports of Mg castings into the EU. Good quality statistics compiled by ACEA on vehicle production, imports and exports in the EU. Assumed growth in use of Mg cast components between 2002 and 2012 equal to that of Al, i.e. 21%. Rounded figures for Mg in Mg cast components to 1 decimal place, in acknowledgement of the associated uncertainties.*

Annex D *Sankey diagrams*

Figure 26: Sankey diagram of flows into and out of the EU's Mg cycle in 2012

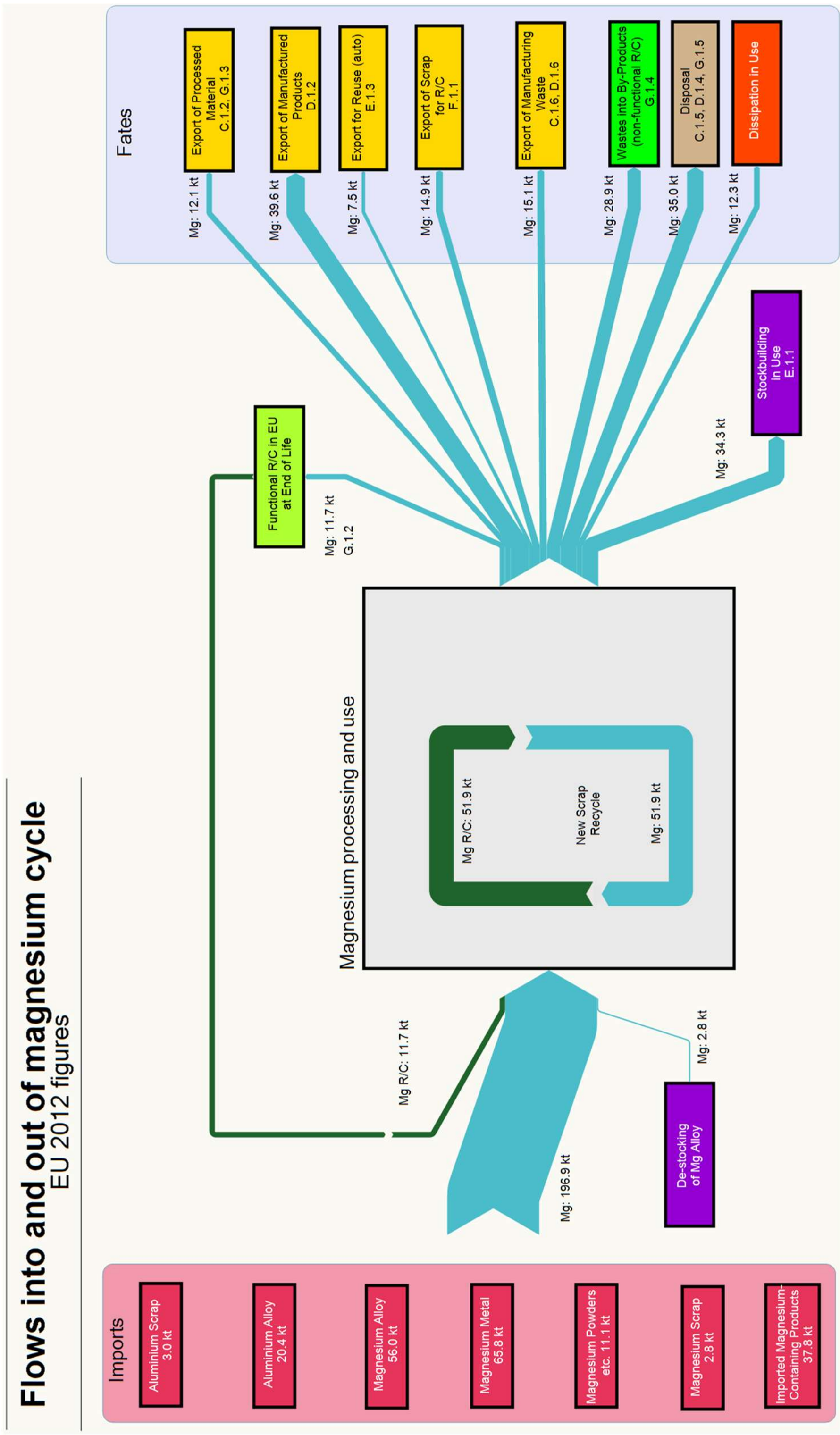


Figure 27: Sankey diagram focusing on the inputs to the Mg cycle, the upstream processing and recycling of Mg as well as the main losses and application sinks

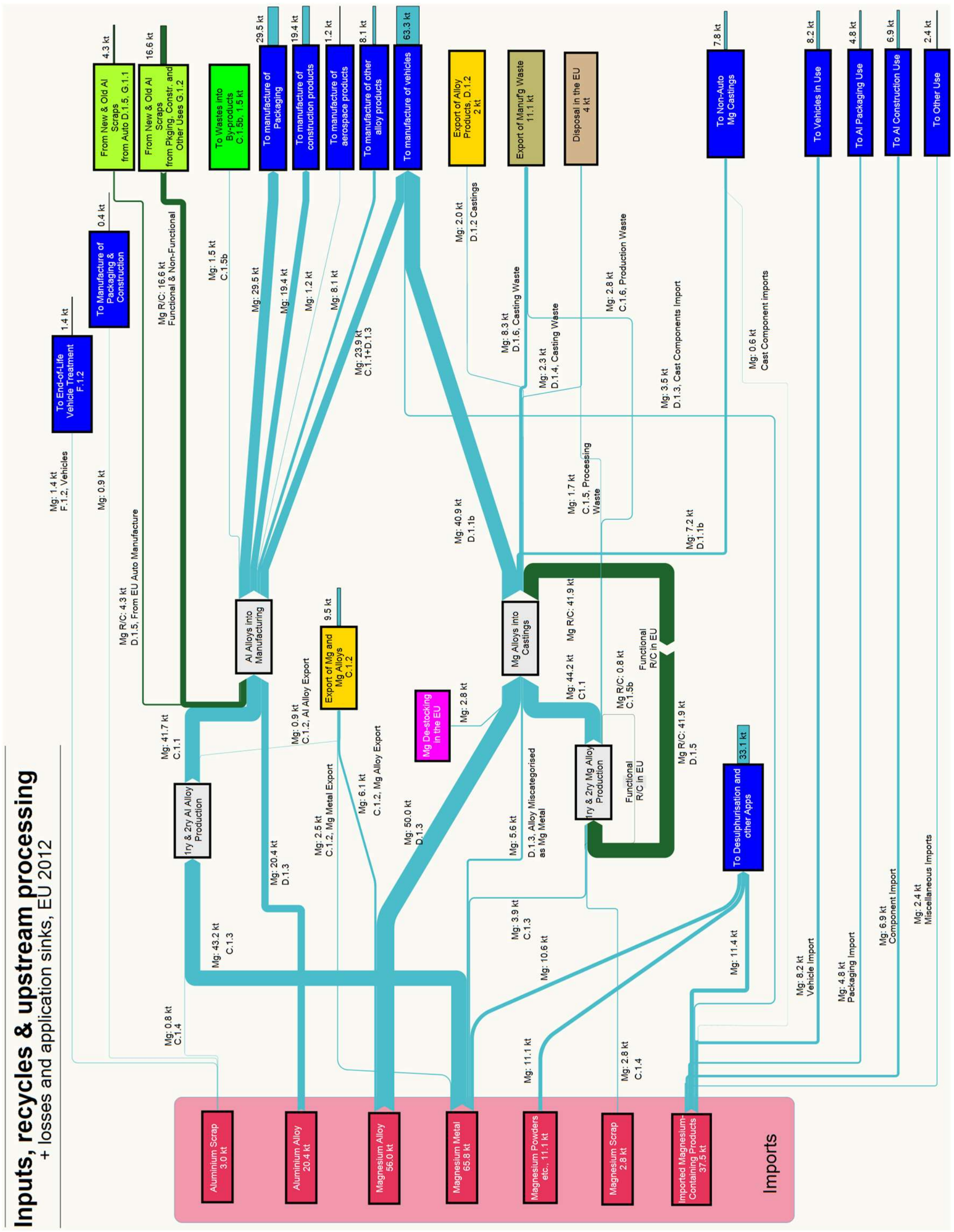


Figure 28: Sankey diagram of the flows related to Mg's use in automotive applications

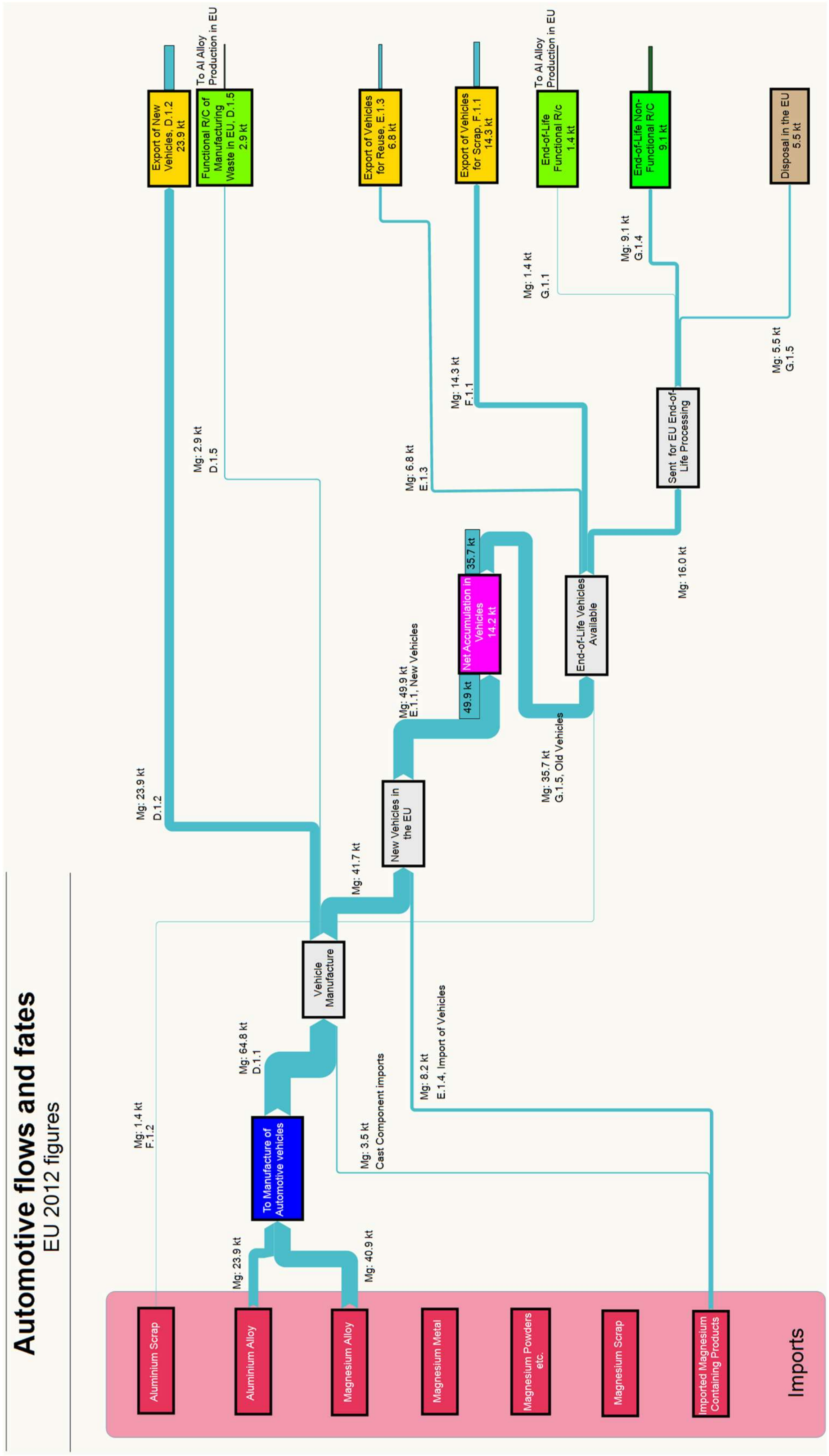


Figure 29: Sankey diagram of the flows related to Mg's use in Al packaging applications

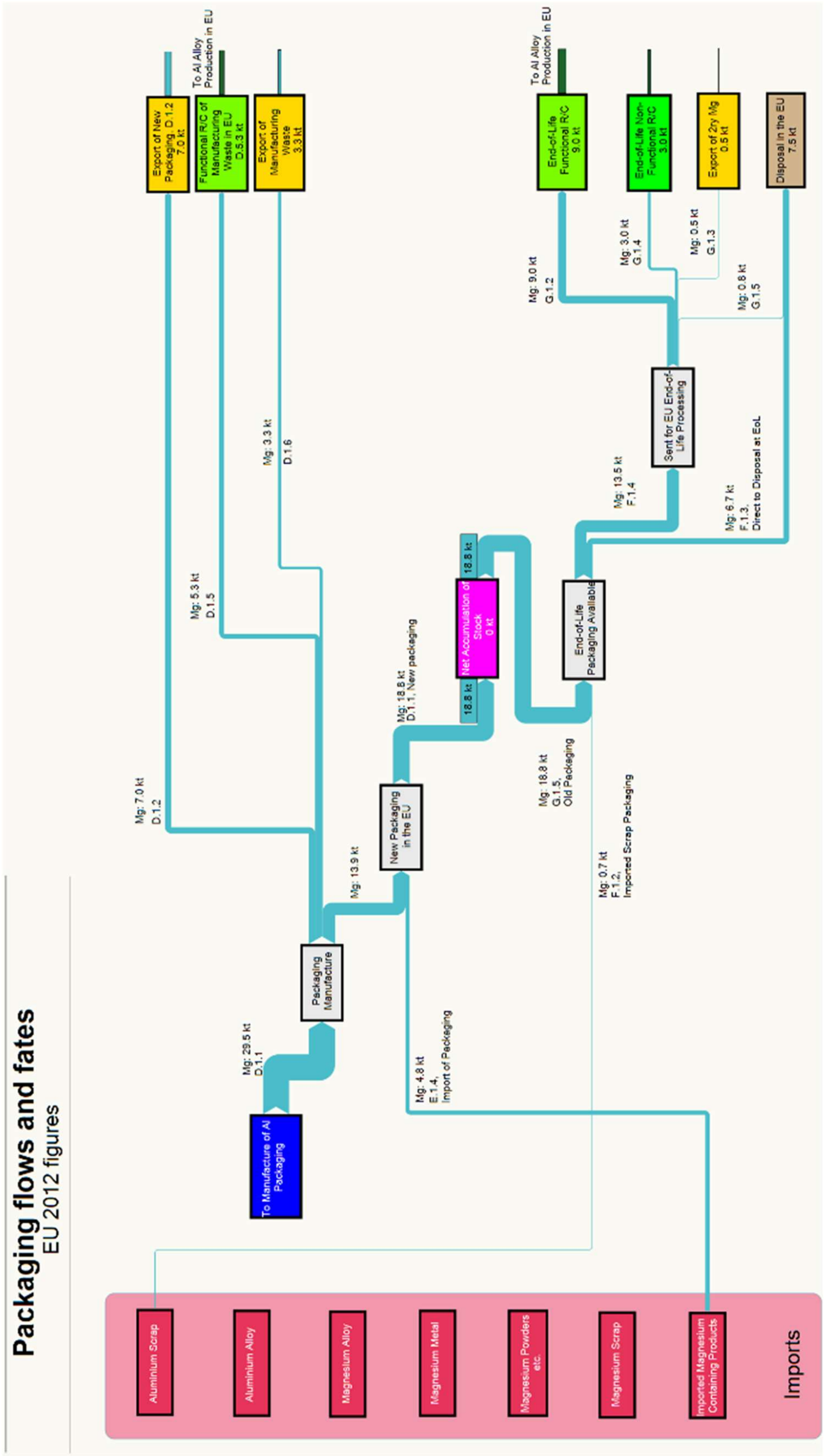


Figure 30: Sankey diagram of the flows related to Mg's use in Al construction elements

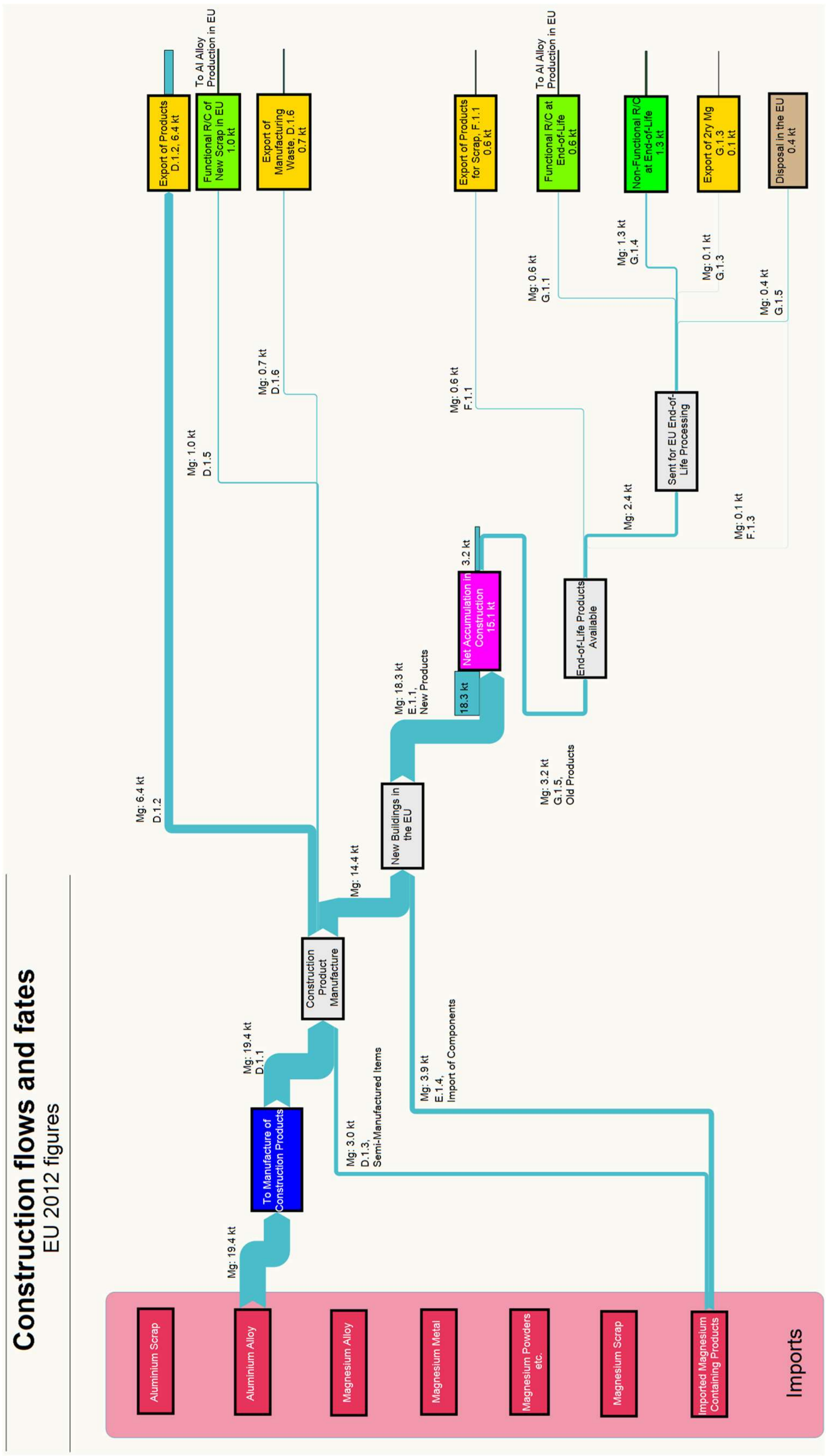


Figure 31: Sankey diagram of the flows related to Mg's use in non-automotive casting, aerospace and other applications of Al alloys

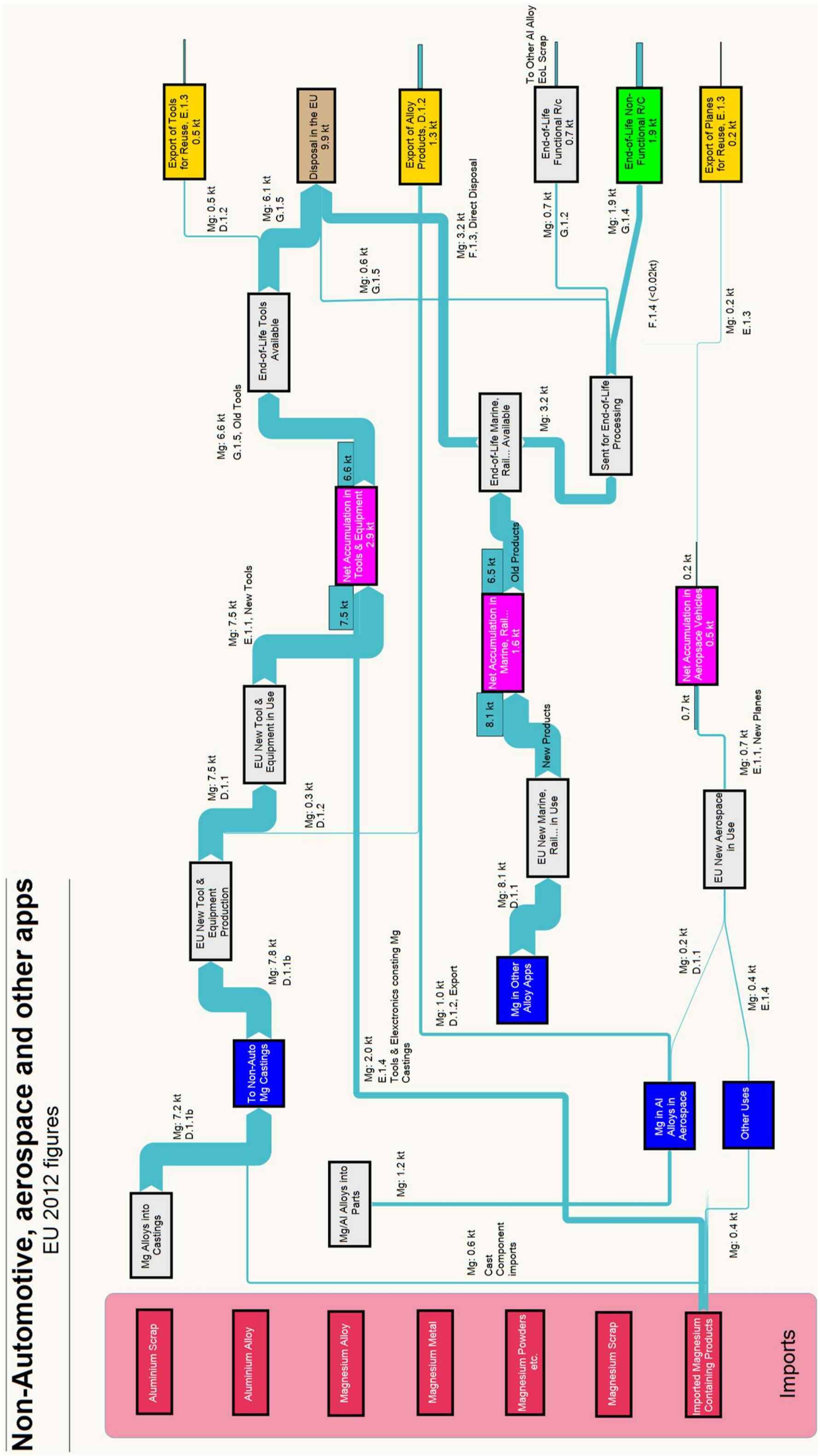
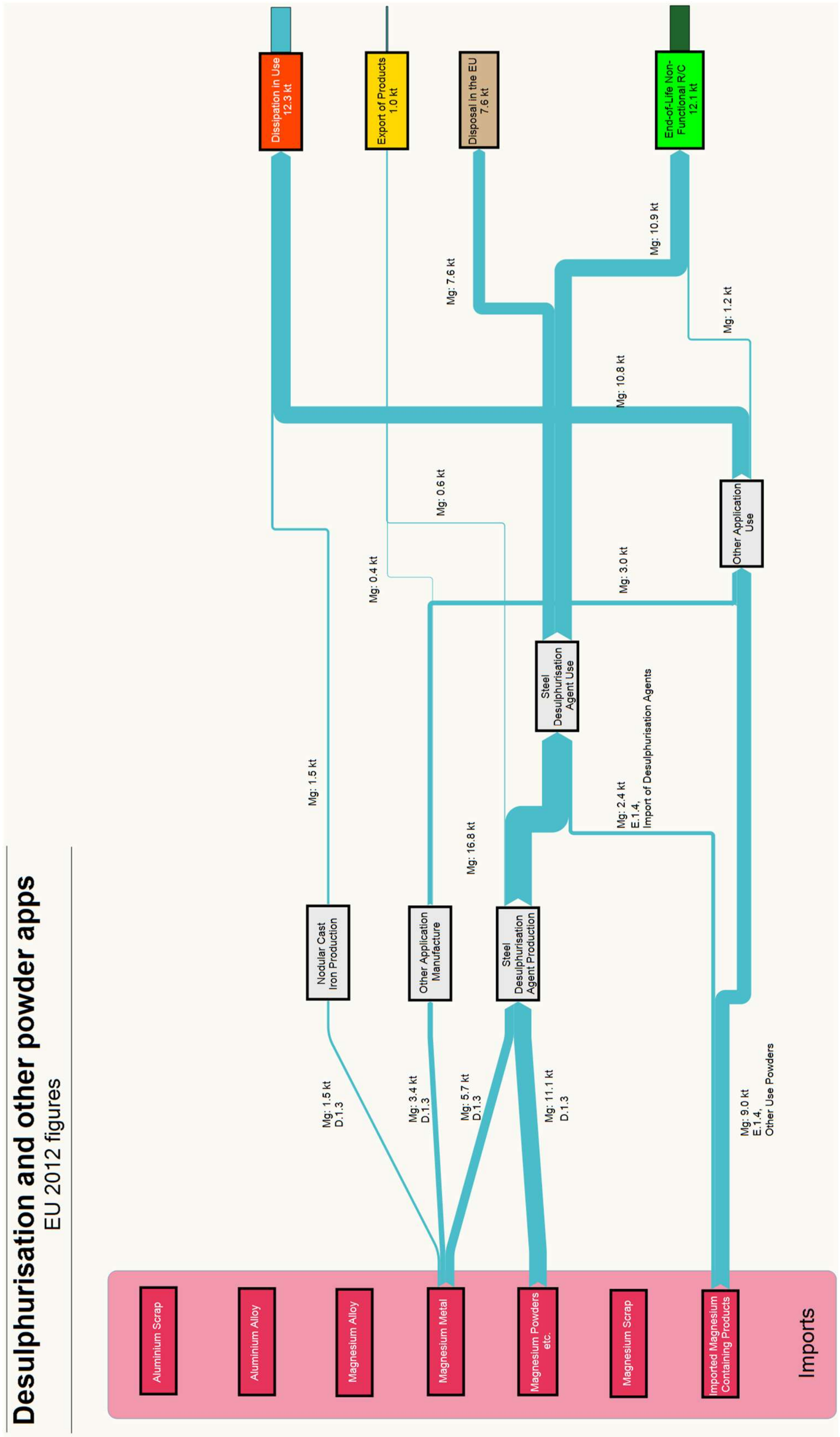


Figure 32: Sankey diagram of the flows related to Mg's use pig iron desulphurisation agents and other 'powder' applications



Nia Bell PhD MPhys, Technical Consultant

With a degree in Theoretical Physics and a PhD in Materials Science, Nia's background is in nanomaterial research at the UCal San Diego and at the NPL, UK. She has a critical and thorough approach to analysing complex technical data sets, and the ability to concisely communicate complex topics. Recent work has been on which metals are critical to the EU defence sector, minor metals by-production, and an EU-wide project to assess the impact of nanotechnology funding.

David Parker MA MBA, Principal Consultant

With a degree in chemical engineering from University of Cambridge, David worked on projects related to waste and resources, working with the UK's Technology Strategy Board, Defra and WRAP. He was instrumental in setting up the Centre for Remanufacturing and Reuse. He has led major collaborative research projects, e.g. for Defra on Business Waste Prevention and for the EC on mineral resources

Rachel Waugh PhD, Technical Consultant

With a PhD in Engineering and an MA in Manufacturing Engineering from the University of Cambridge, Rachel's background is in resource and process efficiency: her PhD explored ways to reduce CO_2 emissions in global steel and aluminium industries, and she has researched emissions reductions in concrete, paper and plastics sectors. Project work includes profiling the remanufacturing industry in Malaysia for the US Government, and remanufacturing batteries for electric vehicles for the TSB.

Oakdene Hollins provides research and consulting services to clients under three main themes:

- Circular Economy
- Sustainable Products
- Enabling Technologies & Materials

For more information visit oakdenehollins.com

OAKDENE HOLLINS
RESEARCH & CONSULTING