Doctoral Thesis

Circular Economy of Packaging Aluminium – An analysis of the current practice and future potential

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Dissertation

Kreislaufwirtschaft von Aluminiumverpackungen - Eine Analyse von Status quo und zukünftigen Verbesserungspotentialen

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Abstract

Aluminium (Al) represents the metal with the highest consumption growth in the last few decades. Beside its increasing usage in the transport (lightweight construction of vehicles) and building sector, Al is used ever more frequently for household goods and packaging material, which represent a readily available source for secondary aluminum due to its short lifetime.

This thesis investigates the extent to which this potential source for recycling of Al is already utilized in Austria and highlights areas for future improvements. Thereto a detailed material flow analysis for Al used in packaging & household non-packaging in 2013 was conducted (Paper 1). Around 3 kg/cap/a (25,000 tonnes) of Al packaging & household non-packaging arose as waste, whereof 39%, are recycled as secondary Al. 26% is regained from separate collection and sorting, 8% from bottom ash (BA) and 5% from mechanical treatment (MT) of mixed municipal solid waste (MSW). A significant amount of Al was lost during thermal waste treatment due to oxidation (10%) and insufficient recovery of Al from both waste incineration BA and mixed MSW treated in mechanical biological treatment plants (49%). Overall it can be concluded that once Al ends up in commingled waste the recovery of Al becomes less likely and its material quality is reduced. Therefore, collection and recovery systems need to increase their efforts to comply with future recycling targets.

Within the Circular Economy Package of the EU, the recycling of Al packaging as a single fraction became a new obligation with mandatory recycling rates of 50% for 2025 and 60% for 2030. It was examined whether the agreed targets are reasonable and realistic within the EU Member States and especially in Austria. Furthermore, it was analyzed which recovery strategy or system (selective collection, deposit refund systems, informal collection, BA treatment or MT of mixed municipal solid waste (MMSW)) seems most promising in reaching targets as well as what the respective recycling rate in the different countries is. To this end, the management of Al packaging in 16 selected European countries, yielding results for 11 countries, were investigated (Paper 2). The results show that six out of 11 countries recycle at least 2/3 of the Al packaging from MSW and only two report very low recycling rates of 20%. The overall recycling rate reported by the different countries cannot be directly linked to the system of recovery. A direct comparison of the recycling rates within the EU Member States,

however, is problematic for several reasons, such as e.g. data are often differently or incorrectly assigned, incomplete or rely on estimations and assumptions.

In a last step it was assessed if and which measures need to be taken to reach the future mandatory recycling rates for Al packaging and which costs arise from these measures. For the case study of Austria, the following measures of Al recovery, and combinations thereof, have been investigated: advanced BA treatment, material recovery facilities (MRF) for MMSW, and changes in the selective collection system (Paper 3). The results reveal that the present recycling rate of 55%[1] for Al packaging in Austria (2018) might be improved most significantly by MRF (up to 94%) and advanced BA treatment (up to 72%). If the only aim were to increase the recycling rates for Al packaging beyond the target of 60%, an improvement in the Al recovery rates from BA treatment would be sufficient. When it comes to increased recycling quantities for all recyclables, in particular plastics, the implementation of complex systems like MRF makes sense, even if this results in higher costs for Al recovery (increasing from today's 480 to 640 €/t of recycled Al).

Keywords: *recycling, aluminium packaging, circular economy, municipal solid waste, selective collection, bottom ash treatment, material recovery facilities*

[1] Differences to the recycling rate 39% determined in paper 1 are due to different year of analysis (2013 vs. 2018), different Al waste (packaging and non-packaging Al from households vs. packaging Al) and different system boundary (eg. Input into smelter vs. output of Al smelter)

Kurzfassung

Aluminium (Al) ist das Metall mit dem höchsten Verbrauchswachstum in den letzten Jahrzehnten. Neben der zunehmenden Verwendung im Transport- (Leichtbau von Fahrzeugen) und Bausektor wird Al immer häufiger für Haushaltsgüter und Verpackungsmaterial verwendet, das aufgrund seiner kurzen Lebensdauer eine leicht verfügbare Quelle für Sekundär-Al darstellt.

Die vorliegende Arbeit untersucht, inwieweit diese potentielle Quelle für das Recycling von Al in Österreich bereits genutzt wird und zeigt Bereiche für zukünftige Verbesserungen auf. Dazu wurde für das Jahr 2013 eine detaillierte Materialflussanalyse für Al in Verpackungen & Haushalts-Nichtverpackungen durchgeführt (Papier 1). Rund 2,96 kg pro Person per Jahr (25.100 t) Al-Verpackungen & Nichtverpackungen aus Haushalten fielen als Abfall an, wovon 39% als Sekundär-Al wiederverwertet werden. 26% werden aus der getrennten Sammlung und Sortierung zurückgewonnen, 8% aus der Schlackenaufbereitung und 5% aus der mechanischen Behandlung. Eine beträchtliche Menge Al geht bei der thermischen Abfallbehandlung aufgrund von Oxidation (10%) und durch unzureichende Rückgewinnung von Al sowohl aus der Schlackenaufbereitung nach der Abfallverbrennung als auch bei der Behandlung von Siedlungsabfall in mechanisch-biologischen Anlagen (49%) verloren. Insgesamt lässt sich feststellen, dass die Rückgewinnung und die Materialqualität von Al abnehmen, sobald Al in gemischtem Siedlungsabfall landet. Daher müssen Sammel- und Verwertungssysteme ihre Anstrengungen verstärken, um zukünftige Recyclingziele zu erfüllen.

Im Rahmen des Kreislaufwirtschaftspakets der EU wurde das Recycling von Al-Verpackungen als separate Fraktion zu einer neuen Verpflichtung mit verbindlichen Recyclingraten von 50% für 2025 und 60% für 2030. Es wurde daher in dieser Arbeit untersucht, ob die vereinbarten Ziele in den EU-Mitgliedsstaaten und insbesondere in Österreich angemessen und realistisch sind. Weiters wurde analysiert, welche Verwertungsstrategie bzw. welches Verwertungssystem (getrennte Sammlung, Pfanderstattungssystem, informelle Sammlung, Schlackenaufbereitung oder mechanische Behandlung von gemischten Siedlungsabfällen) am erfolgversprechendsten erscheint, um die Ziele zu erreichen und wie die jeweilige Al-Recyclingrate in den verschiedenen Ländern ist. Zu diesem Zweck wurde das Management

von Al-Verpackungen in 16 ausgewählten Mitgliedsstaaten der EU untersucht, wobei Ergebnisse für 11 Länder vorliegen (Papier 2). Die Ergebnisse zeigen, dass sechs von 11 Ländern mindestens 2/3 der Al-Verpackungen aus festen Siedlungsabfällen recyceln und nur zwei Länder sehr niedrige Recyclingraten von 20% melden. Die Recyclingraten der verschiedenen Ländern lassen allerdings keine unmittelbaren Rückschlüsse über den Erfolg einzelner Sammlungs- und Rückgewinnungsstrategien (z.B. Pfandsystem, Separatsammlung, Schlackenaufbereitung) zu. Ein direkter Vergleich der Recyclingraten innerhalb der EU-Mitgliedstaaten ist zudem aus mehreren Gründen problematisch, weil die Daten teilweise unterschiedlich oder falsch zugeordnet, bzw. unvollständig sind oder auf Schätzungen und Annahmen beruhen.

In einem letzten Schritt der Arbeit wurde abgeschätzt, ob und welche Maßnahmen im Einzelnen ergriffen werden können, um die zukünftigen verbindlichen Recyclingraten von 60% zu erreichen und welche Kosten durch diese Maßnahmen entstehen. Für das Fallbeispiel Österreich wurden die folgenden Maßnahmen der Al-Verwertung und Kombinationen davon untersucht: optimierte Schlackenaufbereitung, Materialrückgewinnungsanlagen (MRF) für gemischten Siedlungsabfall und Änderungen im System der separaten Sammlung (Papier 3). Die Ergebnisse zeigen, dass die derzeitige Recyclingrate von 55% für Al-Verpackungen in Österreich (2018) am deutlichsten durch MRF (bis zu 94%) und eine verbesserte Schlackenaufbereitung (bis zu 72%) erhöht werden könnte. Wenn das einzige Ziel lediglich darin besteht, die Recyclingraten für Al-Verpackungen auf die geforderten 60% zu erhöhen, wäre eine Verbesserung der Rückgewinnungsmengen von Al aus der Schlackenaufbereitung ausreichend und am kosteneffizientesten. Wenn es darum geht, die Recyclingraten für alle Wertstoffe, insbesondere Kunststoffe, zu erhöhen, ist die Einführung komplexer Systeme wie MRF sinnvoll, auch wenn dies zu höheren Kosten für die Al-Verwertung führt (Anstieg von heute 480 auf 640 €/t Al-Recycling).

Schlagwörter: Recycling, Aluminiumverpackungen, Kreislaufwirtschaft, Siedlungsabfälle, getrennte Sammlung, Schlackenaufbereitung, Materialrückgewinnungsanlagen

List of Appended Papers

Paper 1:

Warrings, R., Fellner, J., 2018. Current status of circularity for aluminum from household waste in Austria. Waste Management 76, 217-224. https://doi.org/10.1016/j.wasman.2018.02.034

Paper 2:

Warrings, R., Fellner, J., 2019. Management of aluminium packaging waste in selected European countries. Waste Management & Research 37, 357-364. https://doi.org/10.1177/0734242X19832368

Paper 3:

Warrings, R., Fellner, J., 2020. How to increase recycling rates. The case of aluminium packaging in Austria. Waste Management & Research https://doi.org/10.1177/0734242X20947

Inhalt

1. Introduction

The world population has grown from 3.7 billion to the current 7.7 billion over the last 50 years. Even though growth rates have declined sharply in recent years, the UN (2019) estimates that 9.7 billion people will populate the earth in 2050.

Among many other factors, this raises the question of the security of supply of raw materials in order to satisfy the demand and production of all kinds of goods for a growing population.

In addition to the fear of shortage or unavailability of raw materials from natural sources, the serious environmental impact of constant production is one of the major challenges of the 21st century. According to the European Commission (EC, 2020) is resource extracting and processing responsible for up to 50% of all greenhouse gas emissions and for more than 90% of biodiversity loss and water stress. The scarcity of raw materials is particularly acute in countries (and communities such as the European Union) that are highly dependent on raw material imports (OECD, 2015).

One way to reduce the consumption of raw materials is to reuse more goods or materials than is currently the case, such as the concept of Circular Economy suggests. Geissdoerfer et al. (2017) define Circular Economy „as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling".

The European Commission has launched a Circular Economy Package (CEP) to protect the climate and the environment and to reduce resource depletion and hence resource dependency. This is to be achieved in conjunction with sustainable economic growth and job creation in the EU (EC, 2014b).

A key approach is the increased recycling and reuse of materials such as metals, plastics, paper or glass. The Member States of the European Union (EU-28) generated 251 Mio. tonnes (t) or 489 kg per capita of municipal solid waste (MSW) in 2018, whereof 35% derived from packaging (EUROSTAT, 2019). The packaging sector in Austria produces around 1.3 million t of packaging waste p.a., which is equivalent to more than 30% of MSW generation (BAWP, 2018) and generates a direct and indirect value added of EUR 4.41 billion, which corresponds to approx. 1.5% of the total domestic gross value added (Tacker et al., 2018). Packaging is usually intended for single use and is rarely reused. Due to the high throughput caused by the short life cycles (e.g. beer cans have a life cycle of 60 days (Coca-Cola, 2020)) and therefore constant reproduction of packaging materials, the recycling of packaging or packaging materials is of particular importance in order to reduce the consumption of primary material.

One of the frequently used packaging materials is aluminium (Al), due to its versatility and outstanding properties, like durability, strength and resistance, lightness, thermal conductivity, barrier properties, food and drink compatibility and aesthetic possibilities (ALFED, 2014).

Primary Al is obtained almost exclusively from bauxite. For this purpose, the Al oxide (Al_2O_3) must be dissolved out of the bauxite and then reduced to metallic Al in an energy-intensive process. Large mining areas for bauxite are located in tropical rainforests, whose clearing for bauxite mining has an impact on the local and global ecology. During the extraction of Al oxide from Al-containing ores approximately 1 to 1.5 tonnes of bauxite residue (red mud) are produced as a waste product for each tonne of Al_2O_3. Due to the content of toxic heavy metals in red mud, improper disposal can cause environmental damage and groundwater pollution (Evans, 2016). As more than 80% of the mine production of bauxite is carried out by 5 countries (USGS, 2019), import dependency, price fluctuations and geopolitical supply uncertainties must be taken into account when considering the availability of primary Al.

The use of secondary Al from recycled and remelted Al scrap instead of primary Al can reduce energy use by 95% and reduce the environmental impacts and economic dependencies mentioned above (Green, 2007). The necessity of recycling Al is also underlined by the steadily increasing demand of +3% annually and a worldwide demand for Al of 70 million tonnes in 2018. Only just over 30% of this comes from recycled Al products (GDA, 2020).

In order to emphasize the need for greater recovery of secondary Al, the EU has amended Directive 94/62/EC on packaging waste. From 2025 a minimum of 55% and from 2030 60% of Al packaging waste must be recycled. Up to now there have been no specific obligations to recycle Al packaging, but only a general obligation to recycle 50% of metal packaging waste

(EC, 2018). The required recycling rates for Al could be a challenging target for some EU Member States (Graedel et al., 2011; Pivnenko et al., 2015). It remains to be seen whether the waste management systems and technologies used are adequate and what measures have to be taken to comply with the legal requirements.

2. Objectives

The main goal of this thesis was to analyze the current status of Al management for Al packaging and household non-packaging in Austria. In particular, improvement potentials were to be identified with regard to the new recycling targets for Al packaging within the framework of the CEP as demanded by the European Commission. However, a look was also taken at the EU Member States to see which recovery strategy or systems for Al packaging are currently applied in these countries. The respective performances in the different countries may allow drawing conclusions on the most promising systems and highlighting the difficulties in comparing the recycling systems and rates between the countries. Finally, an attempt was made to translate the results into concrete proposals to achieve higher recycling rates. Different scenarios have been developed to assess whether and which measures need to be taken to secure future mandatory recycling rates and what the economic costs of these measures will be. For the analysis of the Al management and the development of scenarios for increasing the recycling rates of Al packaging, Austria was used as a case study.

The thesis is structured, as mentioned before, in 3 papers:

Paper 1 analyzed the status of Al management in Austria using the method of Material Flow Analysis (MFA) for determining the material flows of Al packaging & household non-packaging between the different waste management processes in Austria for 2013. In addition, Al packaging & non-packaging products were differentiated according to material thickness. This was to determine the extent to which the wall thickness of Al influences the behaviour of Al in waste treatment and recovery. The results in Paper 1 refer to the total amount of recycled Al packaging <u>and</u> non-packaging from households, while the subsequent Paper 3 with updated data refers exclusively to Al packaging.

Paper 1 aimed at answering the following questions:

- What is the market volume of Al packaging and household Al non-packaging (kg per capita) in Austria in 2013?
- What is the level of rigid, semi-rigid and flexible Al material in packaging?
- What is the composition of the calculated recycling rate, what proportion is accounted

for by selective collection and recovery from waste processing ?

- Does the type of Al packaging & household non-packaging influence the recycling rate?
- Where and to what extent do losses of Al occur?
- Which areas of waste management can be highlighted for future improvement?

In **paper 2**, an attempt was made to extend the inventory of Al management from Austria to other Member States of the European Union. The results of this research should give an overview which waste management strategies and systems are applied in the individual countries. It was further examined whether the agreed targets for the recycling and reuse of Al-packaging within the EU Member States are reasonable and realistic.

The particular research questions addressed in Paper 2 are:

- What is the market volume of Al packaging (kg per capita) in the individual countries?
- What are the recycling rates in the selected EU Member States?
- Are the 2025 recycling targets for Al-packaging are reasonable and realistic?
- Which collection and waste management systems are in use?
- Which recovery strategy or system (selective collection, deposit refund systems (DRS), informal collection, bottom ash (BA) treatment or mechanical treatment (MT) of mixed municipal solid waste (MMSW)) seems most promising in reaching targets?
- Does the correlation between the recovery quantities from the various systems and the overall recycling rate allow instructive conclusions about potential vulnerabilities in meeting recycling targets and help to generate proposals to attain increased recycling rates?

Paper 3 examined six alternative recovery scenarios for Al packaging in Austria, which include measures at different stages/areas of waste management. The scenarios consider adaptation and changes and the use of new processes, in order to achieve higher recycling rates for Al packaging. These scenarios are based on the underlying processes selective collection, BA treatment and material recovery facilities (MRF). Supplementary to the recovery rates achievable by the different scenarios, the respective costs (operating and investment costs) were calculated. The correlation between the Al recycling rates of the chosen scenario and the costs in EUR per tonne of recycled Al packaging could provide meaningful conclusions on the achievement of the potential recycling targets and help to propose the most cost-effective choice. Paper 3 therefore addresses the following questions:

- What measures could be taken in Austria to achieve the mandatory recycling rates for Al packaging by 2025?
- Which of the measures of Al recovery (BA treatment, MRF for MMSW and changes in the selective collection system) are the most promising to reach the targets?
- What economic costs arise from these measures?
- Could the correlation between the Al recovery rates of the selected scenario and the costs in EUR per tonne of recycled Al packaging provide meaningful conclusions about the achievement of potential recycling targets and help in deciding on the most cost-efficient choice?

3. Recycling of waste and packaging waste in Austria and European Union

3.1. Definitions of municipal solid waste and recycling

According to the Eurostat (2017) “Municipal waste consists of waste collected by or on behalf of municipal authorities and disposed of through waste management systems. Municipal waste consists mainly of waste generated by households, although it also includes similar waste from sources such as shops, offices and public institutions”. This therefore includes the same type of waste as garden and park waste (including cemetery waste) or street sweepings, which are not generated by households.

Recycling is understood as “any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes” (EC, 2008).

With respect to Aluminum, this means that the recycling rate represents the ratio of the amount of Al packaging that is selectively collected and/or recovered from BA or by waste processing, such as MT, referred to the amount of Al packaging put onto the market.

3.2. The legal framework for waste and packaging waste

The European Commission launched in 2015 an ambitious EU Action Plan for the Circular Economy (CEP) to protect the environment and natural capital, while promoting jobs, growth and investment. The CEP comprises 54 actions covering the whole range from production and consumption to waste management and the use of secondary raw materials, all translated into legislative and non-legislative measures. (EC, 2015a). A major goal is to “significantly reduce total waste generation and halve the amount of residual (non-recycled) municipal waste by 2030. [...] The legally binding targets in EU waste legislation have been a key driver to improve waste management practices, stimulate innovation in recycling, limit the use of landfilling, and create incentives to change consumer behaviour“ (EC, 2020).

The amendments made to Directive 2008/98/EC on waste and the Directive 94/62/EC on packaging and packaging waste demand a minimum of 55% of MSW and 65% of all packaging waste by the end of 2025. Regarding the specific materials contained in packaging waste, 50% of plastic, 25% of wood, 70% of ferrous metals (Fe), 50% of Al, 70 % of glass and 75 % of paper and cardboard must be recycled by 2025. By 2030 a minimum of 55 % of plastic, 30 % of wood, 80 % of Fe, 60 % of Al, 75 % of glass and 85 % of paper and cardboard is required (EC, 2018). The original proposal for Al was 75% by the end of 2025 (EC, 2015a), but was watered down in the final directive (Kremser, 2018). Up to now there has been no obligation within the EU to separately report recycling rates for Fe and Al packaging, but only a reporting obligation for 50% of overall recycling for metal packaging (EC, 2004). For Austria the new amendment also requires an adjustment to the Austrian Packaging Ordinance 2014 (Verpackungsverordnung, VVO), which specifies a minimum recycling rate of only 50% for metals (Verpackungsverordnung, 2014). Only some Member States have so far reported by type of recycled metal and report data on waste and recycling volumes of Fe and Al packaging to Eurostat.

In addition to the increased recycling rates, other changes and adjustments have been made. To ensure "uniform application of the calculation rules and comparability of data", the calculation points for packaging materials have been specified. The calculation point for metals is defined as sorted metal that is not further processed before it enters a metal smelter or furnace. The Al concentrate from BA treatment must not contain any other materials contained in the metal concentrate such as minerals or other metals. All Al must be derived exclusively from packaging waste (EC, 2019).

3.3. Al packaging & household non-packaging consumption

A potential policy instrument to improve recycling is the so-called extended producer responsibility (EPR). In the European Union, EPR "is mandatory within the context of the WEEE, Batteries, and ELV Directives, which put the responsibility for the financing of collection, recycling and responsible end-of-life disposal […] on producers. The Packaging Directive also indirectly invokes the EPR principle by requiring Member States (MS) to take necessary measures to ensure that systems are set up for the collection and recycling of packaging waste" (EC, 2014a). The manufacturers of packaging must pay a license for the marketed packaging, and waste treatment companies generate revenues from the recovered recyclables (Pires et al., 2011). The market quantity for Al packaging can therefore be determined by the licensed quantities of Al packaging that are reported to Eurostat or national authorities. As there is not yet a reporting obligation for Al packaging, market or waste quantities of Al packaging can also be calculated by selectively collected quantities in conjunction with quantities of Al packaging in MMSW determined on the basis of MMSW sorting analyses. Thereby it can be assumed that waste generation equals the market volume of packaging as packaging is generally disposed of shortly after use and any stocks of packaging can henceforth be neglected. It is also assumed that an informal sector and losses through littering are negligible (see Chapter 3.4 and 4.1.1).

The Al balance for packaging applied in Paper 1 differs from official surveys because it includes all Al used as packaging material and therefore expands the usually Al packaging quantities applied. For instance, in official statistics only packaging containing more than 80% Al is considered as Al packaging. Otherwise the packaging material is classified as composite material and is not officially allocated to Al packaging because the dominant material is mostly plastic or paper (ARA, 2015).

3.4. Collection and waste management systems for Al packaging

The recycling of Al packaging in EU Member States takes place through selective collection, deposit refund system, informal collection, BA treatment from municipal solid waste incineration (MSWI) or MT of MMSW in mechanical-biological (MBT), resp. MT plants. Which collection and waste treatment options are used may vary significantly between the countries. Sometimes only one or two options are applied. The recovery of recyclable materials is determined not only by the type of waste management systems used, but also by the technology used or infrastructure provided.

The Al packaging used is generally collected by bring systems (containers at public places for different fractions), door-to-door collection (containers, bins or bags collected directly at households with regular frequency), a mixture of both and/or DRS (Eunomia, 2011; Seyring et al., 2015). All these systems (besides DRS) collect all types of Al packaging (cans, aerosols, trays, taps etc.) together with other (packaging and often non-packaging) metals. Only very few countries have installed a DRS solely for Al cans, where a deposit fee is additionally charged at the time of sale. The fee is refunded upon return of the can. There is also an informal sector for collection of Al in some countries (Huber-Humer et al., 2018), but not much reliable and usable data is available on this. A considerable part of Al packaging is intentionally or unintentionally disposed of via the MMSW. MMSW is sent for further processing, where it undergoes thermal treatment and/or MBT/MT.

During MBT/MT Al is recovered as Al scrap via eddy current separators (ECS). The ECS are not able to separate the entire metallic aluminium load and the non-recovered Al generated by MBT/MT plants goes to landfills or ends up in the cement industry, where it contributes as refuse-derived fuel (RDF) to the clinker generation.

Al melts during incineration (850°C) at around 660°C and forms Al oxide (Al_2O_3) through the reaction with oxygen. The conversion from Al oxide (Al_2O_3) to Al is economically unfeasible and oxidized Al is considered a loss. The level of oxidation of Al packaging & household non-packaging materials in combustion and re-melting processes depends on the thickness, mechanical resistance and the Al alloy, as well as the temperature during combustion.

All non-combustibles of MMSW remain in the BA and undergo further treatment. The amount of metallic Al present in the BA was determined as the difference between the amounts of Al inserted into waste incineration, on the one hand, and the amount of Al oxidized during combustion and Al present in FA, on the other hand. For the recovery of Al from MBT/MT plants or from BA treatment from MSWI the nature and quality of the technology employed will influence the recovery rate of Al from MBT/MT and BA treatment. The commonly used ECS technology allows detecting and recovering Al lumps larger than 3-4 mm, while smaller ones remain in the residuals. Only very powerful ECS are able to separate significant amounts of Al from the fine fraction (0-6 mm) of BA (Fuchs & Schmidt, 2013), which contains 40-60% of the total Al present in the BA (Allegrini et al., 2014; Berkhout et al., 2011; Biganzoli et al., 2013; Mitterbauer et al., 2009; Steketee et al., 2011; TB Hauer, 2010; Xia et al., 2016). Decisive for the type and scope of the measures and technologies used are not only the legally prescribed recycling rates but also their economic profitability.

The recovered Al scrap from selectively collected packaging & household non-packaging, MBT/MT treatment and BA is fed into melting plants.

4. Materials and Methods

4.1. Al management in Austria

In order to capture, describe and investigate the physical flows of Al packaging & household non-packaging in Austria for 2013 the method of Material Flow Analysis (MFA) (Brunner & Rechberger, 2017) is used. The material flow model presented delineates the different stages of waste management (collection, sorting, treatment and disposal) and the recycling process itself (re-melting) (Figure 1). In practice, the following processes are considered:

- Household Al packaging & non-packaging consumption
- Waste collection and sorting
- Incineration and BA treatment
- Mechanical treatment
- Industrial incineration(cement industry)
- Aluminum smelter (melting plant)
- Al losses
- Landfill

Al in packaging & non-packaging was subdivided into three product groups: rigid, semi-rigid and flexible (López et al., 2015; TB Hauer et al., 2016). The allocation to these categories is based on a survey of a product-related substance flow analysis (ProSFA) for MMSW in Vienna by Taverna et al. (2010). The wall thickness of Al (Table 1) as defining element strongly influences the behavior of Al during waste treatment (e.g., oxidation during combustion, separability via eddy current separator) and affects also the recovery yield of Al scrap in the melting plant (e.g. higher losses for flexible Al).

All data refer to the year 2013. If no data were available, reference data from different times were used and associated with a degree of uncertainty (see Chapter 4.1.3). Unlike packaging, the lifespan of non-packaging is much longer and varies depending on the product. In this thesis, the lifespan of non-packaging as well as its stock buildup was disregarded. Only the annual quantities of discarded non-packaging goods from households into MSW were considered. The determined recycling rate of Al refers to all Al (packaging and household non-packaging) present in MSW.

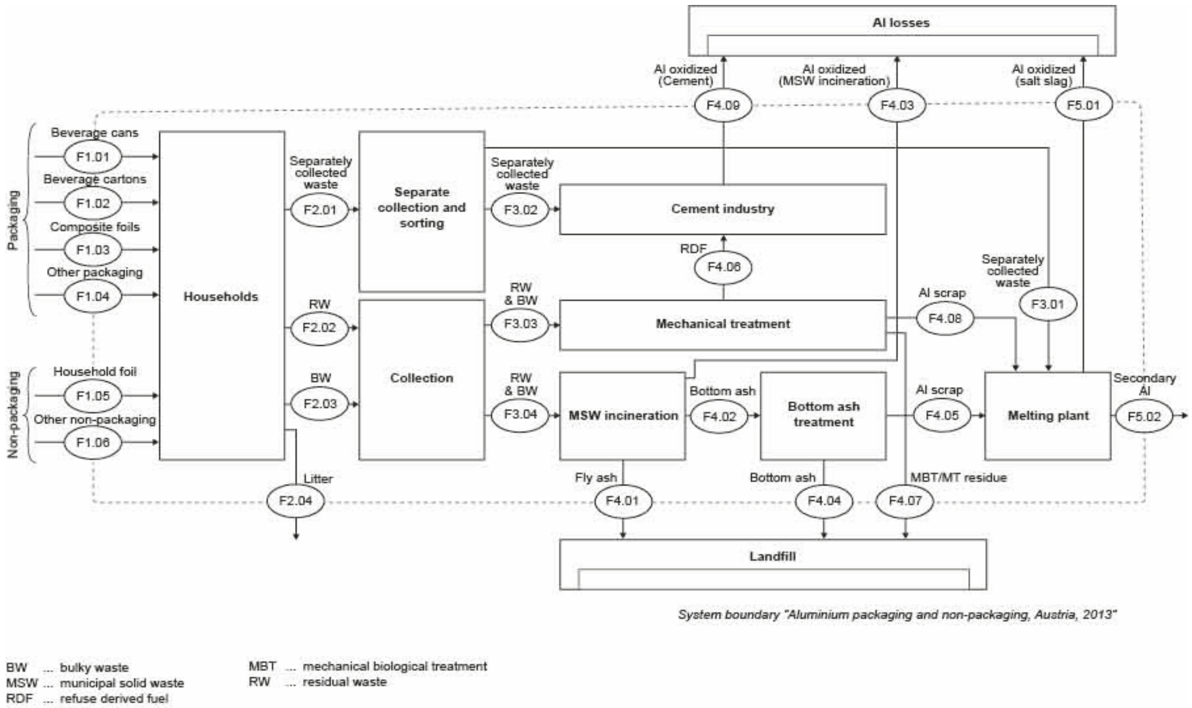

Figure 1. Model overview for Al packaging & household non-packaging management

Table 1. Al in packaging & non-packaging divided by product groups

Product group	Wall thickness	Packaging	Non-packaging
Rigid	> 0.2 mm	beverage and food cans, aerosol containers, etc.	household ware, fittings, coins, kitchen appliance, etc.
Semi-rigid	0.05-0.2 mm	closures, tubes, trays, etc.	freezer containers, tubes or hosts, etc.
Flexible	< 0.05 mm	foil and laminated foil (composite or mono material, e.g. butter or chocolate wrapping)	household foil, coffee capsules, etc.

4.1.1. Generation, recovery and disposal of Al packaging & household non-packaging

Market volume and waste generation

The input flows F1.01-F1.06 describe the amount of Al packaging & household non-packaging used in Austria. Different products were distinguished (beverage cans, beverage cartons, composite foils and other packaging & household non-packaging). The market volume of packaging and waste quantities of household non-packaging was calculated from data of Austria's leading packaging compliance scheme Altstoff Recycling Austria (ARA, 2017), a survey on packaging by TB Hauer et al. (2015) and various waste analyses. The market volume of beverage cans (F1.01) and beverage cartons (F1.02) were based on market volume and collected quantities (ARA, 2017; TB Hauer et al., 2015). Beverage cartons partially contain Al foil (TB Hauer et al., 2016), whereby an average Al content of 4% was assumed (Fachverband Kartonverpackungen, 2017). The market volume of Al composite foils (F1.03) was difficult to identify because no specific data were available and was therefore estimated based on the ProSFA study for MMSW in Vienna by Taverna et al. (2010). These data were compared with a Spanish study by López et al. (2015) and estimates from the European Aluminium Association (EAA, 2017) and the European Aluminium Foil Association (EAFA, 2017). Other Al packaging (F1.04) include Al packaging except beverage cans, foils in beverage cartons and composite foils. Data about their usage in Austria were obtained by a market survey and waste analyses conducted by TB Hauer et al. (2015).

Al household non-packaging comprises household foil and other non-packaging items such as household wares, fittings, tubes, coins, or coffee capsules. The amount of household foil (F1.05) was based on a market analysis from TB Hauer et al. (2015). The volume of other Al household non-packaging (F1.06) was difficult to assess and could only be estimated via various waste sorting analysis (Amt der Kärntner Landesregierung (Ed.), 2012; ARGE Abfallanalyse Oberösterreich 2013, 2014; Boku, 2011; IUT & SDAG, 2014; Land Salzburg, 2013; Salzmann Ingenieurbüro, 2000; TB Hauer et al., 2015; TB Hauer & FHA, 2010; TB Hauer et al., 2016).

Selective collection & sorting

After usage, Al packaging & household non-packaging enter selective collection[2] & sorting systems (F2.01) or end up as MMSW (F2.02) or occasionally as bulky waste (BW) (F2.03). Littering (F2.04) was neglected because intensive and regularly repeated clean-up work by municipalities (Loimayr, 2010) and retained solids at the power stations of Austrian rivers complement common waste collection systems and prevent dissipative losses (Verbund AG, 2017). The selectively collected and sorted Al packaging & household non-packaging, except for beverage cartons and selectively collected composite foils (F3.02), are provided as Al scrap to Al smelters (F3.01). MMSW & BW with the non-selectively collected packaging and non-packaging is sent for further processing, where they undergo thermal (F3.04, 73%) or MT (F3.03, 27%) (BMLFUW, 2014, 2015).

Mechanical treatment

In Austria fourteen MBT/MT plants with a treatment capacity of around 660,000 t (BAWP, 2018) process municipal and commercial waste (CW). For the recovery of Al as Al scrap (F4.08), information was obtained by the operators of MBT/MT plants and a survey conducted by the Federal Environmental Agency of Austria (Neubauer & Öhlinger, 2008). According to MFAs by (Skutan & Brunner, 2005), it is estimated that about 25% of the non-recovered Al generated by MBT/MT plants goes to landfills (F4.07) and 75% is used by the cement industry (F4.06); the Al contained therein is lost for Al recovery (F4.09).

MSW incineration and BA treatment

All non-combustibles remain in the BA and undergo further treatment. The amount of metallic Al present in the BA (F4.02) was determined as the difference between the amounts of Al inserted into waste incineration (F3.04), on the one hand, and the amount of Al oxidized during combustion (F4.03) and Al present in fly ash (F4.01), on the other hand. For the latter (amount of the Al removed via fly ash), the information provided by the biggest operator of waste incineration plants in Austria was used (Wien Energie, 2012). Biganzoli et al. (2012)

[2] The original terms separate collection and residual waste (Paper 1) were replaced by the internationally common terms selective collection and mixed municipal solid waste

determine the losses due to oxidation of Al packaging & household non-packaging during the combustion process with 9.2% for rigid, 17.4% for semi-rigid and 58.8% for flexible material.

In Austria there are eleven incineration plants for MSW with a total annual processing capacity of 2.5 million t (BAWP, 2018). There are significant differences in the recovery of NFe from BA treatment. Some plants do not recover NFe at all, whereas other plants mechanically pre-treat their waste before combustion, but only one of these upstream systems separates NFe. Data from MSWI were only partly available and many incineration plants have heterogeneous waste inputs with significant amounts of commercial and industrial waste. The four waste incineration plants in Vienna burn nearly exclusively MMSW and maintain precise data recording. The processing of the BA from these plants, can be regarded as typical for Austrian waste incinerators. Hence, the corresponding Al recovery (kg Al recovered per tonne of residual waste incinerated) served as a reference value for waste incineration and BA treatment in Austria (Stadt Wien MA 48, 2017). This reference value and data about the amount of MMSW & BW incinerated were used to assess the overall amount of Al packaging and household non-packaging recovered as Al scrap from BA (F4.05). The losses of metallic Al (F4.04) via the landfilling of the BA was calculated from the non-recovered Al from BA treatment.

Al recycling

The recovered Al scrap from collected packaging & household non-packaging (F3.01), MBT/MT treatment (F4.08) and BA (F4.05) is fed into melting plants. During the re-melting process, minor losses of Al occur due to further oxidation (F5.01), which according to the largest Austrian producer of secondary aluminium can be estimated at 3% (AMAG, 2017). The Al regained from the re-melting process is fed back into the Al system as secondary Al (F5.02) and reflects the physically recycled volume of Al.

The MFA model displays all Al oxidation losses as export flows. In reality, however, these flows end up in landfills or final products (e.g. cement), which was not shown in the figure for the sake of clarity.

4.1.2. Data characterization for MFA

The data on material flows in this thesis are based on various data sources, which again are based on different reporting methods. If no information was given, missing data were complemented from scientific investigations or, if needed, using data from similar processes. A characterization of the data uncertainty was conducted in order to evaluate the robustness of the Al flows and model results.

Table 2. Uncertainties. Data quality indicators and assessment criteria (Laner et al., 2016)

Indicator	Score: 1	Score: 2	Score: 3	Score: 4
Reliability	Methodology of data generation well documented and consistent, peer-reviewed data.	Methodology of data generation is described, but not fully transparent; no verification.	Methodology not comprehensively described, but principle of data generation is clear; no verification.	Methodology of data generation unknown, no documentation available.
Completeness	Value includes all relevant processes/flows in question.	Value includes quantitatively main processes/flows in question.	Value includes partial important processes/flows, certainty of data gaps.	Only fragmented data available; important processes/mass flows are missing.
Temporal correlation	Value relates to the right time	Deviation of value 1–5 years.	Deviation of value 5–10 years.	Deviation more than 10 years.
Geographical correlation	Value relates to the region studied.	Value relates to similar socio-economical region (GDP, consumption pattern).	Socio-economically slightly different region.	Socio-economically very different region.
Other correlation	Value relates to the same product, the same technology, etc.	Values relate to similar technology, products, etc.	Values deviate from technology/product of interest, but rough correlations can be established based on experience or data.	Values deviate strongly from technology/product of interest, with correlations being vague and speculative.
Expert estimate	Formal expert elicitation with (empirical) database—transparent procedure and fully informed experts on the subject.	Structured expert estimate with some empirical data available or using transparent procedure with informed experts.	Expert estimates with limited documentation and without empirical data available.	Educated guess based on speculative or unverifiable assumptions.

For the quantitative data, mean values and uncertainties (given by the standard deviation) were calculated, whereby for the latter a normal distribution was assumed. To evaluate the data and assess the resulting uncertainties, a rating scheme with assigned coefficients for various indicators, introduced by Laner et al. (2016), had been applied. Their approach goes back to a data quality assessment scheme introduced by Weidema and Wesnæs (1996) and a data uncertainty assessment of material flows using data classification from Hedbrant and Sörme (2001). In practice, five data quality indicators (reliability, completeness, temporal correlation, geographical correlation and other correlations) were rated on a scoring system from 1 to 4, with 1 ranking the highest (good data quality) and 4 the lowest (poor data quality). The indicator reliability refers to the methodology of the data generation and how well the data were documented and verified. Completeness evaluates all relevant mass flows in question and assesses the extensiveness of the data. Temporal and geographical correlations refer to the consistency and deviation of the data in time and space. The other correlation indicates values related to a different product or technology. Sometimes information relies on expert judgements. In such cases the reliability of the expert's opinion is used as the only indicator (Laner et al., 2016). The uncertainties were quantified by coefficients of variation (CV, standard deviation divided by mean), and aggregating the CV's of the individual indicators established the overall uncertainty of the data. A detailed overview of quality indicators, assessment criteria and calculated uncertainties can be found in Table 2 & Table 3.

Table 3. Uncertainties. Coefficients of variation for the data quality indicators (Laner et al., 2016)

Data quality indicator	**Sensitivity level**	**Score: 1**	**Score: 2**	**Score: 3**	**Score: 4**
		Coefficient of variation (CV, in %)			
Reliability	–	2.3	6.8	20.6	62.3
Completeness temporal geographic other correlation	High	0.0	4.5	13.7	41.3
	Medium	0.0	2.3	6.8	20.6
	Low	0.0	1.1	3.4	10.3
Expert estimate	–	4.5	13.7	41.3	124.6

The STAN (substance flow analysis) software was chosen to balance the input data of the MFA with respect to uncertainties and inconsistent data. The inherent Sankey diagram (Chapter 5.1, Figure 3) displays the thickness of the data flows proportional to their value (Cencic & Rechberger, 2008).

4.2. Assessment of EU targets for Al packaging within Member States

4.2.1. Data on Al packaging in selected countries

Every year, Eurostat publishes data on the amounts of MSW and metal packaging generated and the material and energy recovery rates provided by the individual Member States of the European Union, but no specific data are given by which system the recycled amounts were accomplished. Information on Al packaging will only be required by the end of 2025, but some EU Member States have already voluntarily published data on Al packaging for several years (Eurostat, 2017). The most up-to-date data at the time of completion of this assessment was available for 2015 and/or 2016, so all subsequent data are related to this period. Next to the country reports to Eurostat, information from various Member States within the EU has been retrieved for market volumes and recycling rates of Al packaging. The data used came from official statistics and from waste management authorities that were either publicly available or submitted to the authors upon request. Data from waste treatment companies were omitted because the purpose of this work was not to call into question the information used to calculate the recycling rates. Rather, the differences in official data and the consequent need for a uniform and precisely formulated requirement for data collection should be demonstrated.

This thesis tried to encompass a large number of countries with different collection and waste treatment systems and strategies in waste processing. The first selection was determined by the countries already reporting data on Al packaging to Eurostat (altogether 5 countries). Subsequently, countries were selected that already follow well-developed waste strategies and publish data accordingly. Furthermore, attempts were made to incorporate the various collection and waste treatment systems in the selection of countries. Therefore, the following

EU Member States, as well as Switzerland and Norway, have been selected for further processing, as shown in the list below, including the corresponding data sources:

Austria	(ARA, 2018; BAWP, 2018)
Belgium	(Fost Plus, 2018; OVAM, 2018; StatBel, 2018)
Czech Republic	(Eurostat, 2017; MZP, 2018)
Denmark	(Dansk Industri, 2018; Statbank Denmark, 2018)
France	(ADEME, 2018; Citeo, 2017)
Germany	(Der Grüne Punkt, 2018; DESTATIS, 2017)
Greece	(EOAN, 2017)
Ireland	(Repak, 2018)
Italy	(CiAl, 2017; ISPRA, 2017)
Netherlands	(AFV, 2016; StatLine, 2018)
Norway	(RENAS, 2018)
Poland	(Rekopol, 2018)
Portugal	(Ponto Verde, 2018)
Serbia	(UNS, 2018)
Sweden	(FTI, 2018; Naturvardsverket, 2018; Returpack, 2018)
Switzerland	(BAFU, 2017; IGORA, 2018)
United Kingdom	(DEFRA, 2017)

Unfortunately, it was not possible to obtain all relevant data from Denmark, Norway, Ireland, Switzerland, Serbia and Poland. Hence, the analysis focused in the end on 11 countries only.

4.2.2. National waste management measures for Al packaging

The disposed Al packaging is processed via different collection and waste management systems (selective collection, deposit refund system, informal collection, BA treatment or MT of MMSW), as mentioned in Chapter 3.4. All these systems (besides DRS) collect all types of Al packaging (cans, aerosols, trays, taps etc.) together with other (packaging and often non-packaging) metals. Figure 2 summarizes collection systems for metal beverage cans within different EU Member States (Eunomia, 2011). Only two of the countries surveyed have installed a DRS solely for Al cans. Two countries do not add or report recovered quantities from BA treatment for recycling (Table 4).

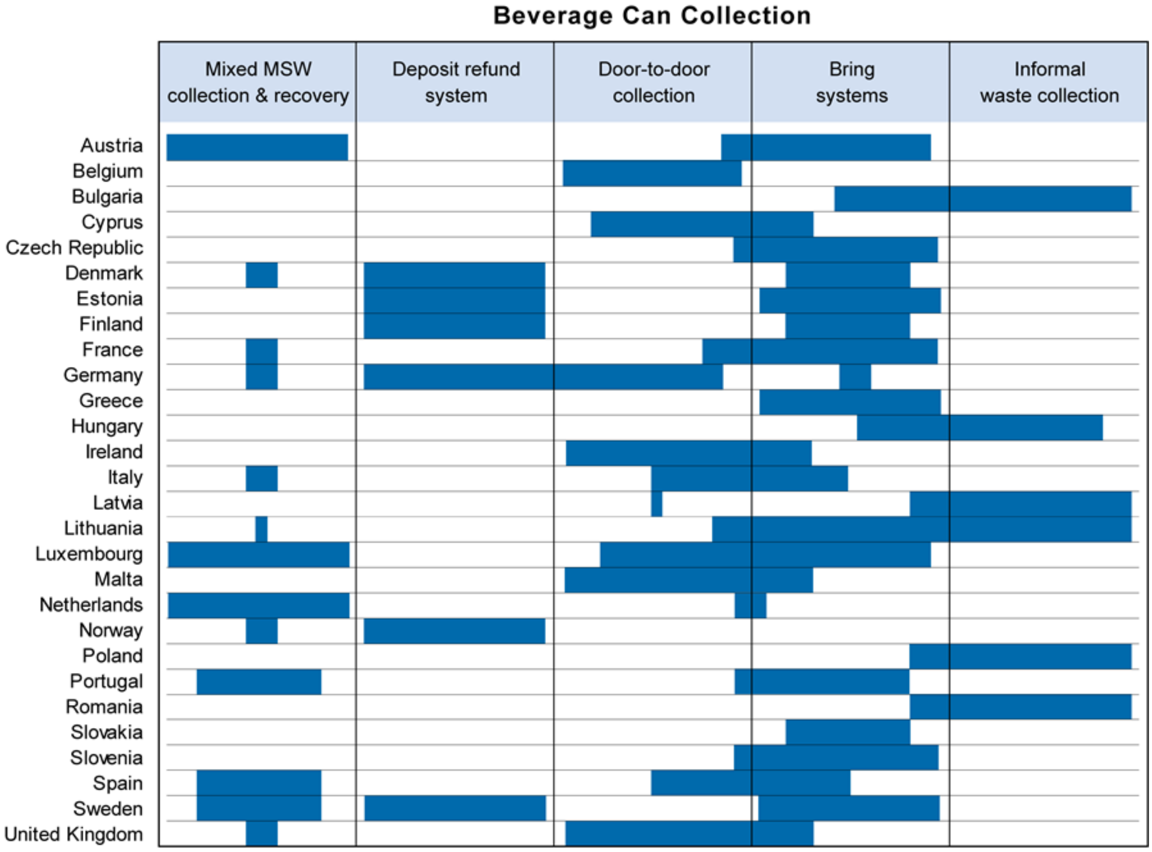

Figure 2. Evaluated waste management scenarios for Al packaging

Table 4. Recovery Al packaging through collection and waste management systems

Country	Recycling of Al packaging through		
	DRS	Selective collection	BA/MT treatment
AT	no	yes	yes
BE	no	yes	yes
CZ	no	yes	-
DE	yes	yes	yes
FR	no	yes	yes
GR	no	yes	yes
IT	no	yes	yes
NL	no	yes	yes
PT	no	yes	yes
SE	yes	yes	no
UK	no	yes	yes

4.3. Scenarios for improved Al recovery in Austria

4.3.1. Description of processes and scenarios

Based on the research of Al management in Austria (see Paper 1) six alternative recovery scenarios (S1 – S6) for Al packaging (see Table 5) have been investigated. They include measures at different stages/areas of waste management:

- Selective collection
- Upstream Materials Recovery Facility (MRF)
- BA processing of MSWI

The first area is an improvement in the selective collection for Al packaging in Austria. The compliance schemes in Austria have implemented knowledge and awareness campaigns for many years, like "ARA4kids", a specific environmental education program for children, or the initiative "Throwing in instead of throwing away" ("Reinwerfen statt wegwerfen"), to improve recycling awareness in the population and prevent littering (ARA, 2019b). At the same time, attempts have been made to optimize the current collection system itself, inter alia, by improving the infrastructure or considering alternative ways of collection. One of these approaches is a changeover from separate metal collection to a mixed collection system (S1, joined metal and light-weight packaging), which will be examined in this paper.

The second option which was assessed is an upstream MRF for MMSW before incineration. Metals can be recovered from BA from MSWI, but to minimize the losses due to inefficient or insufficient recovery technologies or to oxidation processes (see Chapter 3.4), it seems rational to separate recyclables before combustion. This is already done through selective collection of valuables. However, large quantities of recyclables are still disposed of via the MMSW. MRF are automated or semi-automated sorting facilities that separate mixed and co-mingled materials into separate material streams with saleable recyclables and residual streams that contain no or very little recyclable and recoverable materials for final disposal (Cimpan et al., 2015; Pomberger & Küppers, 2017). These facilities are modular systems and can be used for different purposes but are becoming more popular in waste management due to high recovery of secondary raw materials, like plastics, metals, paper, wood and glass, including bio-waste (Dougherty Group, 2006). In this paper, the use of MRF (S2) for MMSW in

Austria is investigated, optionally with retention (S2a) or waiver (S2b) of subsequent BA treatment for the combusted residuals.

The third option is an improvement in recovery of Al from BA treatment. For this purpose, a modified and improved technology for the recovery of Al is considered. The Austrian company Brantner has developed an alternative wet BA treatment process and implemented it on an industrial scale, which enables a higher recovery of metals. The processing consists, next to the commonly used sieving, crusher and eddy current separator (ECS), of a jigger for density separation and sludge dewatering (Stockinger, 2016). This BA treatment method (S3) is used in this paper as an alternative BA treatment to obtain higher Al recovery rates from MSWI BA.

Table 5. Evaluated waste management scenarios for Al packaging

Scenarios		**Al recovery processes**									
S 0	Status Quo	MMSW collection	+	Selective collection			+	MSWI	+	Standard BA treatment
S 1	Mixed Selective Collection	MMSW collection	+	Mixed Selective Collection			+	MSWI	+	Standard BA treatment
S 2a	MRF	MMSW collection	+	Selective collection	+	MRF	+	MSWI	+	Standard BA treatment
S 2b	MRF w/o BA Treatment	MMSW collection	+	Selective collection	+	MRF				
S 3	Advanced BA Treatment	MMSW collection	+	Selective collection			+	MSWI	+	Advanced BA Treatment
S 4a	Mixed Selective Collection + MRF	MMSW collection	+	Mixed Selective Collection	+	MRF	+	MSWI	+	Standard BA treatment
S 4b	Mixed Selective Collection + MRF w/o BA Treatment	MMSW collection	+	Mixed Selective Collection	+	MRF				
S 5	Mixed Selective Collection + Advanced BA Treatment	MMSW collection	+	Mixed Selective Collection			+	MSWI	+	Advanced BA Treatment
S 6a	MRF w/o Selective Collection	MMSW collection		-	+	MRF	+	MSWI	+	Standard BA treatment
S 6b	MRF w/o Selective Collection & w/o BA Treatment	MMSW collection		-	+	MRF				

In addition to these three scenarios (S1-S3), the possibility of combining different processes was considered, like combining MRF installation and mixed collection (S4) or MRF and advanced BA treatment (S5). It was also examined whether installing MRF would make a selective collection obsolete (S6). In connection with the installation of MRF, it was also examined whether a subsequent BA treatment is useful or necessary (S2b, S4b & S6b). All scenarios are summarized in Table 5**.**

4.3.2. Costs of collection and waste management systems

Next to the recycling rates achievable by the different scenarios, the respective costs (operating and investment costs) were calculated. The correlation between the Al recovery rates of the selected scenario and the costs in EUR per tonne of recycled Al packaging could provide meaningful conclusions about the achievement of potential recycling targets and help in deciding on the most cost-efficient choice. The recycling of Al packaging involves costs that can vary from one system to another, depending mainly on the type of plant, the technology used and the quantities processed. Essentially, these are composed of capital (CAPEX, costs for the construction of the facility, land, infrastructure and acquisition costs for the required machinery and vehicles and others) and of operational costs (OPEX, for personnel, energy, maintenance, service and other operating costs) (Bohm et al., 2010). In all collection and waste management systems examined, other recyclables (Fe, other no-ferrous, paper, plastic, etc.) next to Al are treated. The specific costs for the recovery of the individual recyclables were calculated by multiplying the overall costs of the respective treatment process by the share of the revenues of the individual recyclable in relation to the total revenues generated. This allowed the net costs (difference between costs for the recovery of the individual recyclable and its revenues for the sellable scrap) for the recovered Al packaging to be determined. For selective collection (ARA, 2019a), MMSW collection (Stadt Wien MA 48, 2019) and MSWI (Brunner et al., 2015), only net costs were available. For a better comparison, the costs and revenues for the different scenarios were calculated per 1 tonne of recycled Al packaging.

The net costs of Al (in €/t Al) for the specific scenarios were calculated by multiplying the net costs of the individual processes by the amounts of Al treated in the respective processes and divided by the total amount of recycled Al. The underlying information was provided by the plant operators or taken from the literature (ARA, 2019a; Brantner, 2019; Bunge, 2015; Cimpan et al., 2015; Environment Media Group, 2020; Pressley et al., 2015; Stadt Wien MA 48, 2019; Stockinger, 2016).

4.3.3. Sensitivity analysis

The calculation of net costs and recycling rates is based on input values that represent the most likely or expected values. Changing these parameters can lead to different results. A sensitivity analysis was carried out to assess the influence of input values on the output values of the scenarios. A Monte Carlo Simulation with 10,000 iterations was performed for each scenario using the software MS Excel® and @Risk 7.6 (Palisade, 2018). Using regression analysis, it was possible to identify the input parameter whose change has a significant influence on the output values. The correlation coefficient of the regression model provides information about the size and direction of the relationship between two variables (see Table 8, Chapter 5.3). The closer the correlation coefficient is to +1 or -1, the stronger the two variables are related positively or negatively. The coefficient of determination R^2 is a statistical measure of how well the regression predictions approximate the real data points. The closer the certainty measure is to 1, the higher is the quality of the regression predictions. In addition to determining regression coefficients, it was examined how the net costs of the different scenarios change with a variation in the input parameters up to +/- 30% of the initial value.

5. Results

5.1. MFA results for Al packaging & non-packaging from households In Austria

The results of the MFA are presented in Figure 3. The market volume of Al packaging & household non-packaging was estimated at 25,100 ± 2,120 t (2.96 ± 0.25 kg/cap/a) according to surveys on packaging volume in Austria 2013 and MMSW analyses of Al non-packaging. This figure was made up of 17,700 ± 670 t (2.09 kg/cap/a) of Al found in MMSW & BW (F2.02 & F2.03) plus 7,400 ± 800 t (0.87 kg/cap/a) of selectively collected Al (F2.01). The main use (45%) of Al in households was for beverage cans. Significant differences were found between the market volume (11,300 ± 250 t) and the collected volume of beverage cans (via selective and commingled waste collection), amounting to 800 ± 210 t. It was assumed that these missing quantities were also selectively collected and sorted, but not included in official statistics as these quantities were managed largely by scrap traders (not displayed in Figure 3).

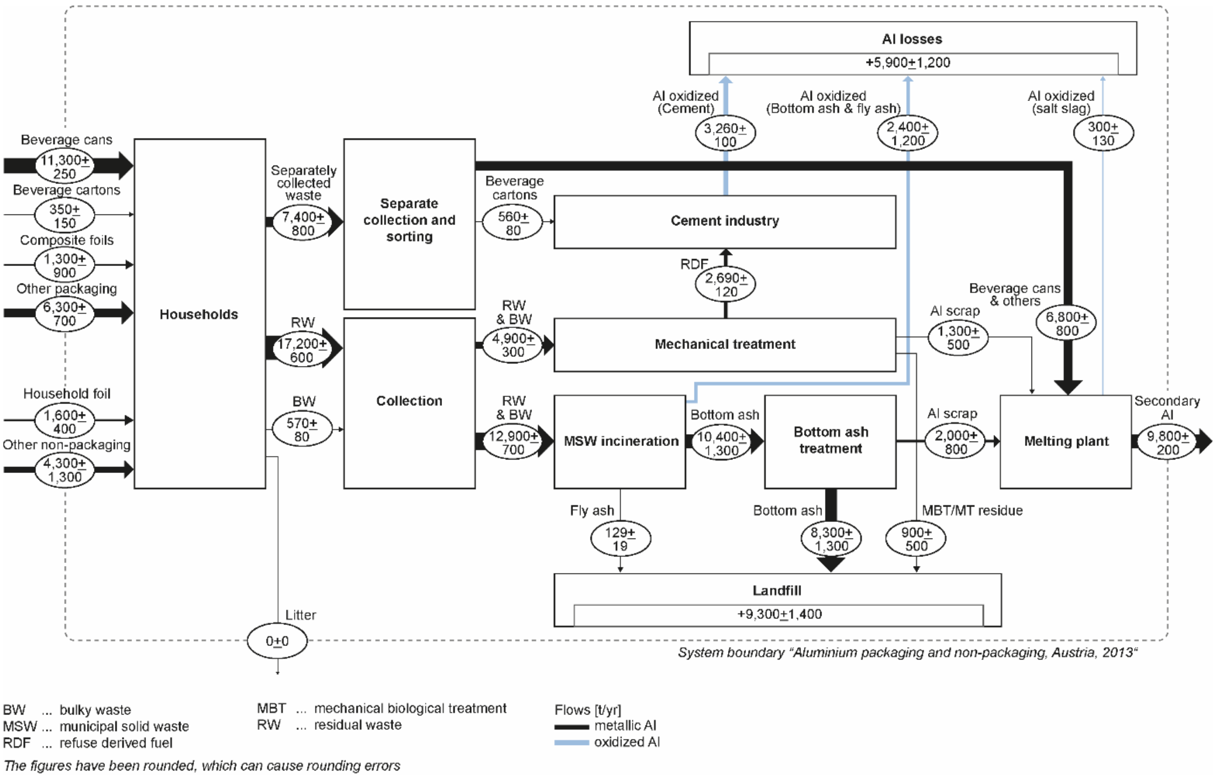

Figure 3. MFA results. Al packaging & non-packaging from households for Austria (2013)

1,600 ± 920 t of Al foil was used in composite packaging material (1,300 ± 910 t Al foil in composite material and 350 ± 150 t in beverage cartons). The part of Al foil in composites that was collected selectively (600 ± 80 t) was sorted out and lost as these quantities are not recyclable and are sent into industrial incineration. There Al oxidizes and finally ends up as Aluminum oxide in cement.

The remaining packaging & household non-packaging quantities (F1.04, F1.05 and F1.06) arose from other Al packaging (6,300 ± 670 t, all products but beverage cans and foils) and household non-packaging (5,900 ± 1.340 t), of which 1,600 ± 400 t were household foil.

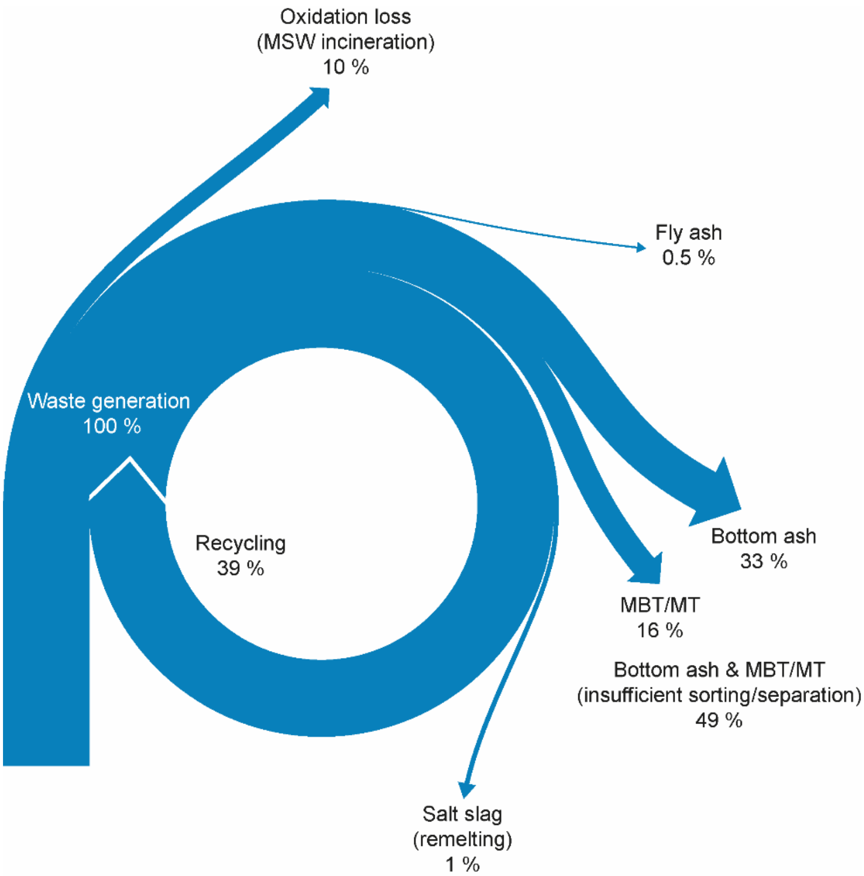

Figure 4. Circular representation of Al packaging & household non-packaging, Austria 2013 (All flows leaving the circle represent losses of metallic Al. Al losses due to the utilization of RDF in the cement industry are allocated to MBT/MT – note that recycled Al is usually not applied in the packaging sector).

The Al in MMSW & BW was further processed, after which 3,300 ± 890 t of Al was recovered as Al scrap. The main share came from BA treatment (2,000 ± 760 t), while the recovery per t waste input from MBT/MT is significantly higher (2.85 kg Al per t waste input) than from MSWI with subsequent BA treatment (1.74 kg Al per t waste input). These higher recovery rates for MBT/MT plant might be explained by the fact that a significant amount of Al oxidizes during incineration and is thus not available for metal recovery. The recovered Al from waste processing (MBT/MT and BA treatment) and selective collection is remelted (10,100 ± 1.220 t) and largely regained as secondary Al. Only minor amounts of Al (300 ± 130 t) are lost (oxidized) in the melting plant.

Overall, about 39% ± 4.8% (9,800 t ± 1.190 t) of the Al present in packaging & household non-packaging are currently recycled and utilized as secondary Al, of which 26% is regained from selective collection and sorting (6,600 ± 800 t), 8% from BA (2,000 ± 760 t) and 5% from MBT/MT treatment (1,200 ± 470 t). The main losses occur through oxidation (2,400 t ± 1,220 t) during waste combustion and owing to insufficient recovery of Al from MSWI BA (8,400 ± 1,300 t) and MMSW & BW treated in MBT/MT plants (3,500 t ± 510), as shown in Figure 4.

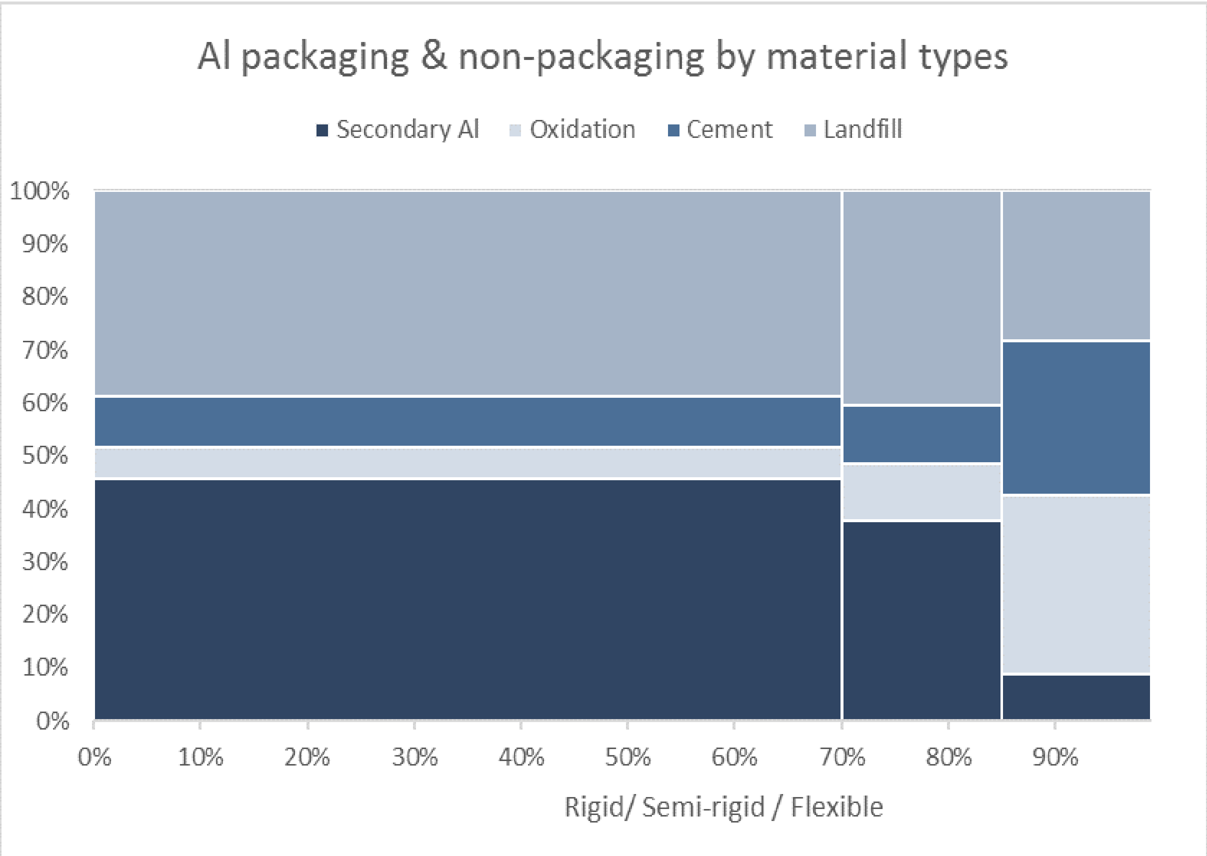

Figure 5. Recycling & losses of Al packaging & household non-packaging, Austria 2013

The type of Al packaging & household non-packaging has a very considerable influence on the recycling rate: 82% (8,100 ± 1.700 t) of the total recycled quantities come from rigid packaging & household non-packaging, while only 3% (300 ± 70 t) of the total recycled Al derives from flexible materials. The results thus show a positive correlation between recycling rates and increasing thickness of the Al material utilized: 46% of rigid and 38% of semi-rigid, but only 9% of the flexible Al material is recycled (Figure 5). The main losses occur for rigid (6,200 t ± 1,350t) and semi-rigid (1,400 t ± 300 t) material during BA treatment (64%, resp. 58%), while the main factor for losses of flexible Al materials is oxidation during waste incineration (37%).

Detailed information about the material flows of Al packaging & household non-packaging at the level of product groups is presented in Figure 6. Besides the fact that thicker Al products are more likely to be recycled, the figure also highlights that 11% of the total Al (2,700 ± 1,230 t) ends up as oxide in the cement industry. There Al oxide is of use for the final product cement, whose typical Al_2O_3 content varies between 4 to 8%. Considering an average content of Al oxide in clay of 16% (raw material and most important Al carrier for the cement production), the “unwanted” utilization of Al packaging & household non-packaging in the cement industries may substitute almost 40,000 t of clay per year (Schneider et al., 2011).

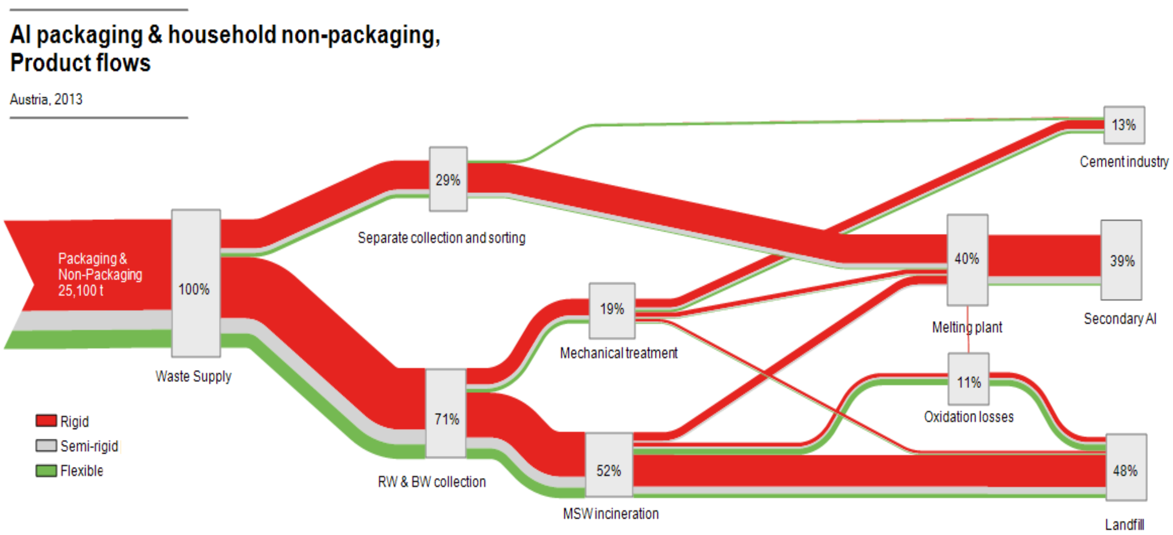

Figure 6. Material flows of Al packaging & household non-packaging at the level of the product groups rigid, semi-rigid and flexible.

For the present thesis, this "alternative" utilization of Al, however, has not been accounted for the recycling rate as only the recovery of metallic Al was considered. This is not only in line with official waste statistics, but is also justified by the fact that the huge energy amount embedded in metallic Al, which is one of the major reasons for Al recycling, is lost during utilization in the cement industry.

5.2. Recycling of Al packaging in selected EU Member States

This thesis examined the management of Al packaging in 16 selected European countries, with results for 11 countries. The quantities consumed of Al packaging were between 9,000 t (Portugal) and 180,000 t (United Kingdom, UK), resp. between 0.9 (Portugal) and 2.7 (UK) kg per capita per year (Figure 7). A correlation between the use of Al packaging and GDP could not be established. Countries with a lower GDP consume more (Greece 2.0 kg/cap/a) or less (Czech Republic 1.3 kg/cap/a) than average (1.6 kg/cap); the same applies to countries with a higher GDP (Sweden 2.7 kg/cap/a) and Germany (1.4 kg/cap/a).

The results show that six out of 11 countries recycle at least 2/3 of the Al packaging from MSW and only three report very low recycling rates of 20-35%, as displayed in Figure 8.

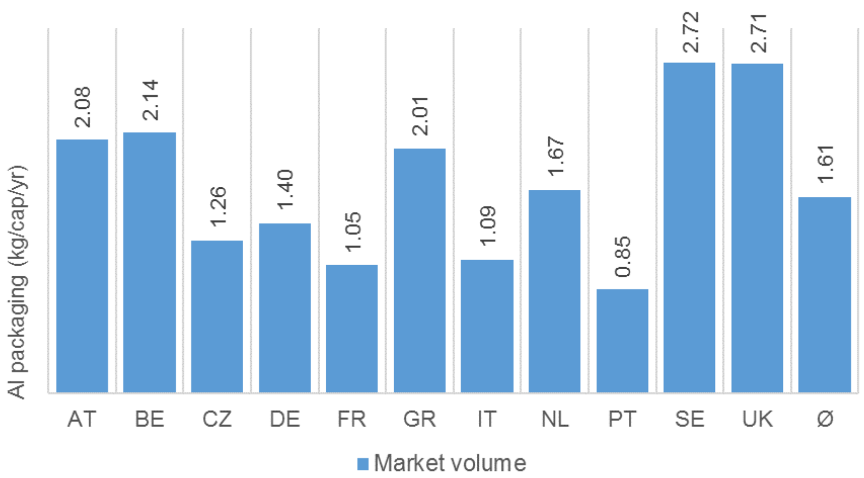

Figure 7. Consumption of Al packaging in selected EU Member States (data given in kg Al/cap/yr)

Germany (88%), the Netherlands (79%), Sweden (77%) and Belgium (76%) achieve very high recycling rates, whereby only Germany, next to Sweden, uses a DRS for Al beverage cans.

These two countries have the overall highest collection rates (DRS and selective collection), but other countries with similar recycling rates make up for it with high amounts of Al recovered from BA treatment.

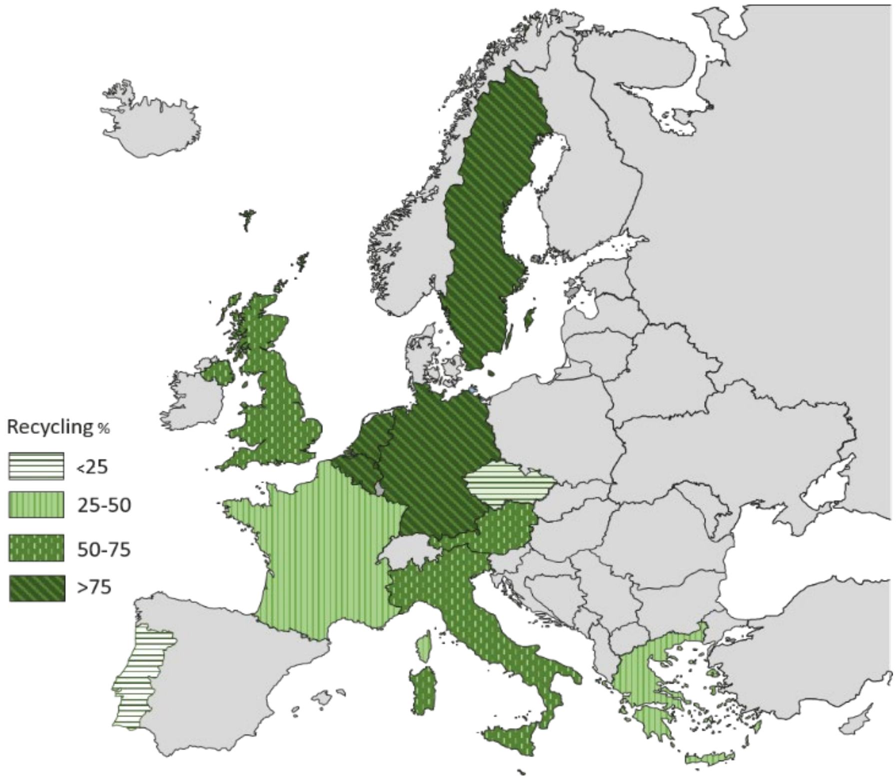

Figure 8. Recycling rates for Al packaging in selected EU Member States (in %)

Hence, based on the available data it can be concluded that countries were able to achieve a high recycling rate for Al packaging either through a very high return rate from the selective collection or elaborate processing of MSW (BA treatment and/or MT) (see Figure 9).

Low recycling rates cannot be directly linked to the type of collection and waste treatment. EU studies show that less developed selective collection systems can be associated with low recycling rates (Seyring et al., 2015). Certainly, a generally low recycling rate of Al packaging can be correlated to rather high rates of landfilling (50-84%). On the other hand, the six countries with the highest recycling rates (except Italy) only landfill 1-3% of their MSW.

No overall correlation could be demonstrated between consumption and recycling rates, as for example Germany (1.4 kg/cap) and Portugal (0.9 kg/cap) have a low consumption rate, while Germany has a high (88%) and Portugal a low (20%) recycling rate. The UK, on the other hand, has a high consumption rate (2.7 kg/cap) and a medium recycling rate (51%). However especially in the two countries with the smallest recycling rates (Czech Republic, Portugal), a low per capita consumption (0.9-1.3 kg/cap) can be observed.

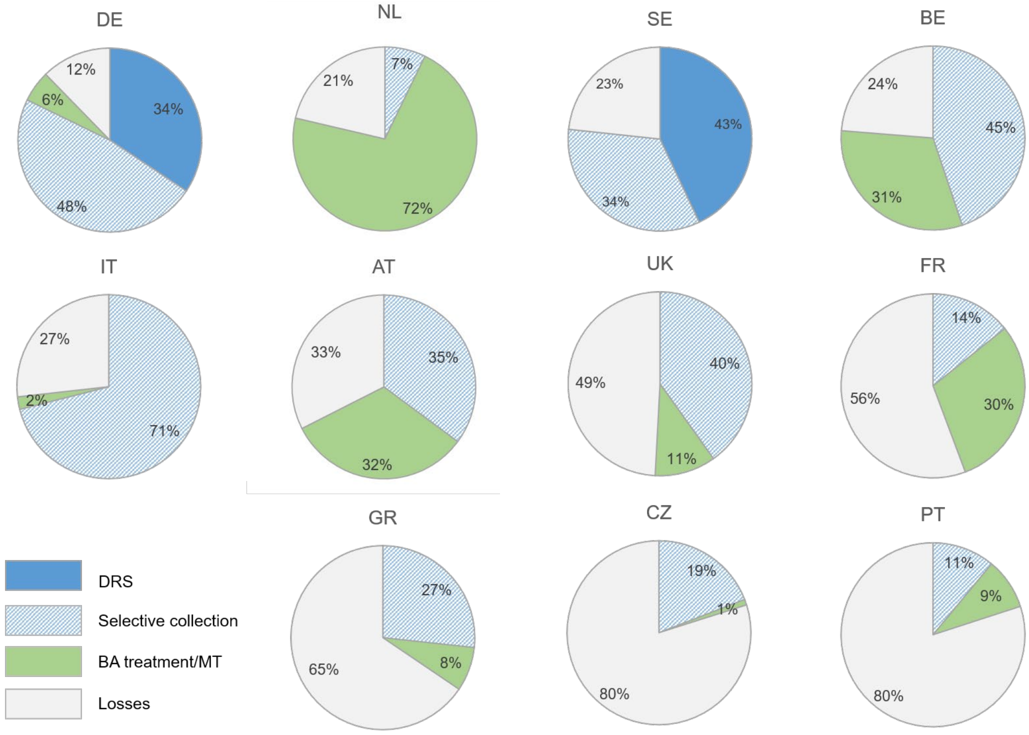

Figure 9. Losses and recovery of Al packaging through different systems in selected EU Member States (in %)

A direct comparison of the recycling rates within the EU Member States is, however, problematic for several reasons, as e.g. data are often differently or incorrectly assigned, incomplete or rely on estimations and assumptions. Hereinafter, a few aspects should be addressed.

Individual countries interpret the somewhat vague definition of MSW (see Chapter 3.1) differently. Some countries consider only waste from households as MSW, whereas other countries also include similar waste types coming from other sources such as waste from parks and streets, offices or commercial and industrial activities. These waste streams are either added to varying degrees to municipal waste or not, depending on the design of the waste collection system. This can lead to different volumes of MSW generation in the Member States

(EEA, 2013), but also to deviant results in national statistics through the different allocation of these waste streams, leading to divergent recycling results.

In some countries, thermal treatment of MSW is widespread and waste incineration capacities are higher than the domestic production of combustible waste. Therefore, considerable quantities of waste are imported into such countries and out of those countries for which it is advantageous to be able to reduce their waste volumes going untreated to landfills. This leads to changed recycling rates both in the exporting country with a lower waste volume and in the importing country with a higher recycling rate (Eunomia, 2011). A report on waste capacities by Wilts and Gries (2015) assume that countries like the UK, Italy, Ireland, France and Finland export MSW to the extent of “up to 6% of their respective incineration capacities”, while other countries (Belgium, Luxembourg and Sweden) need to import waste “in order to keep their incineration capacities at sufficient utilization rates”. In Austria in 2015 99,000 t of MSW were imported and mechanical (pre)treated or combusted, while 78,000 t were exported (BlgNR. 7840/AB XXV.GP, 2016).

The option to recover metals from MT or, more frequently, from BA treatment is used by many countries. For the Al quantities recovered, it is often assumed that all metals present in bottom ashes from waste incineration originate from metal packaging, which is false, because the waste fed into incineration plants contains packaging and non-packaging Al (OVAM, 2018).

The same applies to the assumption that the ashes processed originate exclusively from MSW incinerated. However, most plants also utilize significant quantities of commercial and industrial wastes. In Austria e.g. in MSWI plants 2.4 Mio. t of waste was combusted in 2015, of which only around 1.7 Mio. t came from MSW (BAWP, 2018).

It is also important to note that the quantities recovered from BA treatment or MT are often based on estimations of average recovery yields for metals instead of annually achieved actual recovery quantities. Sometimes the reported yields simply refer to the recovery potential (Schüler, 2017). These estimations are measured differently in each country, depending on particle size and degree of separation. In the Netherlands it is e.g. assumed that 77% of non-ferrous metals larger than 5.6 mm are recovered (AFV, 2016), while in Austria 50% recovery of particles larger than 4 mm is assumed (TB Hauer, 2010).

The input quantities of Al packaging within the EU Member States can also vary because sometimes commercial and industrial packaging is included and sometimes not.

The Al quantities recovered are generally gross amounts, which include impurities, adhesives or moisture. The share of these non-related materials often seems to be larger than the legally allowed 10%. The quantity of recycled Al packaging decreases therefore significantly if such adhesions and metals that do not originate from packaging waste are excluded when calculating the recycling quantities. Literature reviews show that the amount of non-related materials in selective collection, sorting and recycling processes is 10-13% for non-ferrous household goods and 60-70% for Al packaging (Brunner et al., 2015). The EC therefore established “rules for the calculation, verification and reporting of the weight of materials or substances which are removed after a sorting operation and which are subsequently not recycled, based on average loss rates for sorted waste” (Official Journal L 150, 2018). Furthermore, it is unclear to what extent non-packaging Al waste is delivered to collection points, resp. how much Al from packaging is collected and recycled through informal collection and does not find its way into official records. The absence of a well-organized collection scheme leads to illegal littering and increased sorting mistakes in bins or containers (Seyring et al., 2015).

In the future, the output of any sorting operation has to be reported “as the weight of the municipal waste recycled [which] is sent into a final recycling process” (EC, 2015b). A report by Eunomia (2014) “has indicated that currently the point at which Member States report the quantity of metals recycled varies across countries, and includes the following approaches:

- Material collected for recycling
- Output from sorting plants
- Materials sent from scrap dealers to reprocessors
- Materials received at smelting plants”.

5.3. Scenarios for increased recycling rates of Al packaging in Austria

The total mass of waste Al packaging in Austria in 2018 amounted to 20,100 t/a, whereof 36% was selectively collected and 19% recovered from BA processing from MSWI. The recycled amount of Al packaging was therefore around 11,200 t or 55% (S0). These results relate purely to the recycling of Al-packaging, while the results published in Paper 1 (see Chapter 5.1) refer to the status of Al management and recycling rates for Al from MSW, thus for the total amount of recycled Al packaging and household non-packaging. Paper 1 includes furthermore composites that contain Al but are not allocated to Al. The data was updated from 2013 to 2018.

Six scenarios (S1-S6) were investigated to see if they would increase the recycling rates of Al packaging compared to the system actually applied. All of the scenarios investigated lead to an increase in recycled Al volumes. These scenarios were based on the underlying processes selective collection, BA treatment and material recovery facilities A change to mixed selective collection would increase the proportion of Al packaging recovered via selective collection from 36% to 39% (7,200 to 7,800 t/a). The use of an advanced BA treatment instead of conventional BA treatment would raise the recovery of Al packaging from BA from 37% to 66% (4,000 to 7,100 t/a), which would be 19-20% of the total Al packaging waste, respectively 33-35% of the overall recycled quantities, depending on whether a switch to mixed selective collection is included.

According to Pressley et al. (2015) MRF recycles 87% of Al packaging from the MMSW, which corresponds to 54-56% of the total recycled volume if selective collection is used. The outcomes of the scenarios examined (S1-S6) show significant increases of recycled Al packaging (see Table 6) compared to the status quo (S0).

If MRF (S2, S4, S6) is used, up to 94% (19,100 t/a) of the total Al packaging could be recycled. The total abandonment of selective collection when MRF is installed (S6) would drop the recycling of Al packaging to 91% or 18,300 t/a (S6a), respectively 87% (17,500 t/a) if no BA treatment is used (S6b). The type of selective collection in combination with MRF (S2 & S4) has no impact on the recycling rate. The implementation of advanced BA treatment leads to

71% (S3), respectively 72% (S5, with mixed selective collection) of Al packaging recycled (14,300-14,500 t/a). If the only measure is to switch to mixed selective collection (S1), this will only result in a slight increase in the recycling rate of 2% (57% or 11,600 t/a). For some of the scenarios, the transfer coefficients for Al are exemplarily shown in Figure 10.

Table 6. Recycling of Al packaging in different scenarios

Scenarios		Al packaging recycled	Recycling rate
		t/a	%
S 0	Status Quo	11,200	55%
S 1	Mixed Selective Collection	11,600	57%
S 2a	MRF	19,000	94%
S 2b	MRF w/o BA Treatment	18,500	92%
S 3	Advanced BA Treatment	14,300	71%
S 4a	Mixed Selective Collection + MRF	19,100	94%
S 4b	Mixed Selective Collection + MRF w/o BA Treatment	18,600	92%
S 5	Mixed Selective Collection + Advanced BA Treatment	14,500	72%
S 6a	MRF w/o Selective Collection	18,300	91%
S 6b	MRF w/o Selective Collection & w/o BA Treatment	17,500	87%

The net costs of recycling 1 t Al packaging are currently € 480 (S0). These net costs include all costs and revenues of all processes which contribute to or are necessary for the recovery of Al packaging. Hence, the net costs of the different scenarios are also based on all costs and revenues of the individual processes (see Table 7). The latter are summarized as net costs for each process.

All calculations include the costs for the collection of MMSW (114 €/t Al) and the costs for MSWI (100 €/t Al) in the case that Al is recovered via BA treatment. These costs for MSWI were then added to the costs for Al recovery from BA treatment. This also explains why the net costs for conventional BA treatment (670-690 €/t Al) are the highest of all process net costs. In the case of advanced BA treatment, the net costs drop to 130-150 €/t Al simply due to the fact that higher total recovery rates of metals also reduce the net costs for Al recovery.

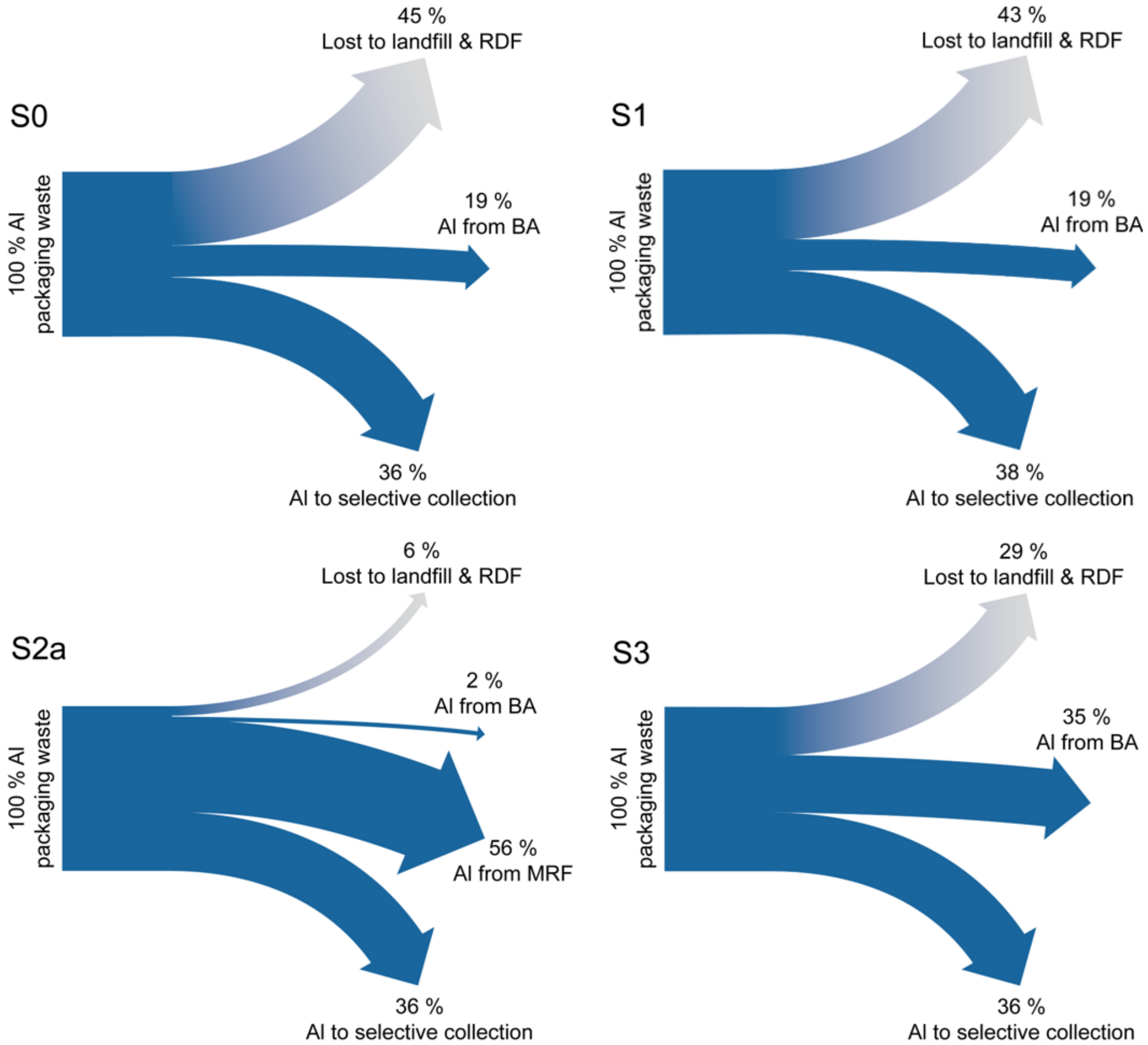

Figure 10. Transfer coefficients of Al packaging for different scenarios (S0, S1, S2a and S3)

In contrast, an MRF treatment prior to waste incineration and subsequent BA treatment increases the net costs for BA treatment up to 2,700-2,840 €/t Al due to the low content of metals present in BA and thus the low revenues achievable by their recovery. The process net costs for selective collection decrease from currently 380 to 340 €/t Al if switched to mixed selective collection. This switch to mixed selective collection is anyway necessary in order to increase the recycling rates for plastics packaging. The net costs for the recovering of Al packaging from MMSW through MRF are 590 €/t Al.

As mentioned above, the net costs for Al (in €/t Al) for the specific scenarios were calculated by the net costs of the individual processes and the quantities of recycled Al (in t Al) related to the total quantity of recycled Al through the individual processes.

Table 7. Costs and revenues of Al recycling for the different processes (given in €/t Al recovered)

		Scenarios	Status Quo	Mixed Selective Collection	MRF	MRF w/o BA Treatment	Advanced BA Treatment	Mixed Selective Collection + MRF	Mixed Selective Collection + MRF w/o BA Treatment	Mixed Selective Collection + Advanced BA Treatment	MRF without Selective Collection	MRF w/o Selective Collection & BA Treatment
			S0	S1	S2a	S2b	S3	S4a	S4b	S5	S6a	S6b
		Unit										
MMSW	Net costs MMSW collection	€/t Al	114	114	114	114	114	114	114	114	114	114
MMSW	Al present in MMSW	t/a	13,000	12,400	13,000	13,000	13,000	12,400	12,400	12,400	20,100	20,100
MRF	Costs of MRF	€/t MMSW			50	50		50	50		50	50
MRF	Annual input in MRF	t/a			1,439,700	1,439,700		1,439,700	1,439,700		1,439,700	1,439,700
MRF	MRF share Al/ total revenues	%			15%	15%		15%	15%		15%	15%
MRF	Al present in MRF	t/a			13,000	13,000		12,400	12,400		20,100	20,100
MRF	Al transfer coefficient MRF	%			87%	87%		87%	87%		87%	87%
MRF	Sales price of Al from MRF	€/ t Al			500	500		500	500		500	500
MRF	Net costs Al from MRF	€/ t Al			590	590		590	590		590	590
BA	Net costs MSWI	€/ t Al	100	100	100		100	100		100	100	
BA	Al present in MSWI	t/a	13,000	12,400	1,700		13,000	1,600		12,400	2,600	
BA	Costs BA treatment	€/t BA	28	28	28		30	28		30	28	
BA	BA quantity	t/a	300,600	300,600	206,200		300,600	206,200		300,600	206,200	
BA	BA share Al/ total revenues	%	26%	26%	26%		26%	26%		26%	26%	
BA	Al in BA	t/a	10,700	10,200	1,400		10,700	1,300		10,200	2,200	
BA	Al transfer coefficient BA treatment	%	37%	37%	37%		66%	37%		66%	37%	
BA	Sales price Al from BA treatment	€/ t Al	600	600	600		600	600		600	600	
BA	Net costs Al from BA treatment	€/ t Al	670	690	2,700		130	2,840		150	1,640	
Collection	Al packaging waste	t/a	20,100	20,100	20,100	20,100	20,100	20,100	20,100	20,100	20,100	20,100
Collection	Al transfer coefficient - selective collection	%	36%	39%	36%	36%	36%	39%	39%	39%		
Collection	Net costs Al from selective collection	€/t Al	380	340	380	380	380	340	340	340		
	Scenario Net costs	€/t Al	480	450	570	510	260	540	480	250	640	590
	Recycling rate for Al	%	55%	57%	95%	92%	71%	95%	92%	72%	91%	87%

The results of the analysis indicated that of all scenarios investigated, the lowest net costs for Al recycling can be achieved by implementing scenario S5, where Al recovery is based on mixed selective collection and advanced BA treatment. The net cost would decrease from 480 to 250 € per 1 t of recycled Al. A change to mixed selective collection without any other measures (S1) would only slightly reduce the net costs to 450 €/t Al recycled. The installation of MRF would result in the highest net costs (S2, S4 & S6), ranging between 480 and 640 €/t Al recycled. Abstaining from Al recovery via BA treatment in the respective scenarios (S2b, S4b & S6b) would reduce the net costs by 10-15%. The use of MRF without selective collection of Al packaging has the highest net costs of all scenarios (S6) at 590-640 €/t per 1 t recycled Al. In order to make Al recovery from MRF competitive with recovery from advanced BA treatment, the treatment costs for MMSW in MRFs would need to drop from 50 €/t to about 30 €/t processed waste. All calculations on MRF are based, among others, on a very high transfer coefficient (87%) for Al recovery, which was reported by the companies building MRF plants. If the transfer coefficient for Al recovery of MRFs only corresponded to the transfer coefficient of advanced BA treatment of 66%, the net costs for Al recovery from MRFs without BA treatment would increase by 160-250 €/t to 680-940 €/t Al recycled. This would also reduce the recycling rates for Al packaging from 91-94% to 78-79%, respectively 66% without selective collection.

Table 8. Regression coefficients for the most relevant input parameters with respect to the net costs of Al recovery for the different scenarios (R^2 is between 0.988 and 0.993)

	S0	S1	S2a	S2b	S3	S4a	S4b	S5	S6a	S6b
Al transfer coefficient BA	-0.73	-0.71	-0.03		-0.71	-0.03		-0.70	-0.04	
Al transfer coefficient collectio	0.01	-0.02	0.24	0.22	0.31	0.25	0.23	0.31		
BA share Al/ total revenues	0.38	0.40	0.08		0.28	0.08		0.29	0.05	
Costs BA	0.38	0.40	0.08		0.28	0.08		0.29	0.05	
Sales price BA	-0.40	-0.40	-0.02		-0.50	-0.02		-0.49	-0.02	
Al transfer coefficient MRF			-0.47	-0.56		-0.46	-0.55		-0.51	-0.61
Costs MRF			0.56	0.53		0.56	0.53		0.56	0.53
MRF share Al/ total revenues			0.56	0.53		0.55	0.53		0.56	0.53
Sales price MRF			0.29	-0.27		-0.29	-0.27		-0.29	-0.27

Input values (transfer coefficient, process costs, share Al revenue relative to total revenues, sales price) have a significant influence on the output values (net costs of scenarios). In all scenarios without MRF (S0, S1, S3 & S5), which are based on selective collection and BA treatment, the transfer coefficient for the recovery of Al from BA treatment has the highest influence on the net costs (Table 8). There is a negative correlation between recovery rate and net costs, indicating that a decrease in the recovery rates of Al leads to an increase in net costs for its recovery and vice versa. Thereby, it does not matter what type of selective collection or BA treatment is used. The regression coefficients for costs and sales price for Al from BA treatment and the share of revenues from Al relative to total revenues are moderate. There is only a very weak relationship between the Al transfer coefficient for selective collection and the net costs when conventional BA treatment is in use, but it becomes more important with advanced BA treatment.

In scenarios with MRF (S2, S4 & S6), the input parameter related to the MRF process (transfer coefficient, costs, sales price and share of Al revenues) all have a similar moderate influence on the net costs of the scenarios, while the influence of the transfer coefficient for selective collection is weak. The R^2 is for all parameters between 0.988 and 0.933, indicating a good model fit and that variations in the output values can be well explained by variations in the input values.

6. Conclusions

This thesis showed, that around 25,100 t of Al household packaging & non-packaging (2013), respectively 20,100 t from Al packaging (2018) have been used in Austria. The first research for the year 2013, which provided an overview of the circular economy for Al from household waste in Austria, showed that 39% is recycled as secondary Al, of which 26% is recovered from selective collection and sorting, 8% from BA and 5% from MT. The second, specific study on the requirements for recycling rates for Al packaging according to the CEP guidelines for 2025 (50%) shows, that the binding targets in Austria have already been reached in 2018 with 55%, but need to be improved in order to reach the targets of 60% by 2030.

While selectively collected Al (67%), especially beverage cans, contribute the most to recycling, the main losses of Al occur through oxidation (11%) during incineration and because of limited recovery from subsequent processes or other sorting constraints (49%). Thereby material thickness plays an important role for Al recovery. Thicker material as used in rigid and semi-rigid products shows higher collection and sorting rates, resp. recovery rates from waste processing. The latter is caused by lower oxidation rates and losses from MSWI BA and MBT/MT treatment.

The investigations in the present thesis have shown that if Al is not collected selectively and enters the subsequent waste treatment processes, its recovery becomes less likely and its material quality decreases. As measures for improved selective collection seem to be limited or only bring about marginal improvements, investments in better separation technologies (separation of NFe from BA and MBT/MT) appear to be essential to achieve a significant increase in the recycling rate of Al.

Here, the use of advanced BA treatment offers a cost-effective solution that can achieve recycling rates of over 70% for Al packaging. BA processing plants are comparatively simple and therefore not very expensive to implement, as they are designed exclusively for the recovery of metals. The installation of MRF prior to MSWI is the most effective way to achieve very high recycling rates for Al packaging (over 90%), but it is associated with high costs because the construction and operation of such systems is rather complex and involves the use of a wide range of technologies. Due to the large number of recyclables and the associated revenues, the net costs per 1 t Al can be kept low on the whole but still have the highest net costs of all scenarios (up to 640 €/t Al recycled). Manufacturers of MRFs report very high recovery rates (87%), while studies on various existing plants show very different recovery rates. According to Cimpan et al. (2015), the potential efficiency of these plants with regard to Al recovery is between 29 and 95%. The installation of MRF, provided the high efficiency reported by the manufacturers is guaranteed, would allow high recycling rates to be reached, not only for Al packaging but also for other waste materials such as plastics packaging. However, based on the results of the present study, the installation of MRF cannot substitute for selective collection of Al packaging as this would result in higher costs and lower recycling rates. MRF can be regarded as complementary recovery option in addition to selective collection.

Table 9. Recycling rates and net costs of scenarios investigated and related to the individual processes (given in €/t Al recovered)

Recycling Process/Scenario	<60%	60-70%	70-80%	80-90%	>90%
Status Quo (S0)	480 €/t				
Mixed selective collection (S1)	480 €/t				
Advanced BA treatment (S3,S5)			250 to 260 €/t		
MRF (S2,S4,S6)					480 to 640 €/t

In summary, it can be said that if the only aim were to increase the recycling rates for Al packaging in Austria beyond the recycling target of 60%, an improvement in the recovery from BA treatment would be sufficient, which, as mentioned, would entail comparatively little effort and cost. Waste management scenarios including MRF would achieve much higher recycling rates (91-94%, see Table 9), but only if the transfer coefficients for Al recovery from MRF correspond to the manufacturers' specifications. Otherwise, they are at the level of advanced BA treatment facilities (>70%).

Part of the thesis was also an investigation of the situation in 2015/16 regarding the recycling management of aluminium packaging in the European Member States. The EU recycling targets, which are mandatory under the CEP for Al packaging (50%) by the end of 2025, have already been met by a majority of the Member States investigated. Only two out of 11 surveyed countries lagging behind by more than 15% ten years before the deadline. The purpose of this study was to identify possible relationships between different waste management systems and quantities recycled from the various systems (separate collection, DRS, informal collection, BA treatment or MT of MSW) in order to eventually draw conclusions about best practices. Based on the reported data, it was not possible to draw any conclusions about a relationship between recycling rates and collection, resp. waste treatment systems in place. It only seems permissible to assert that a DRS together with selective collection leads to a higher overall collection rate. This does not necessarily lead to a higher recycling rate, but reduces the likelihood of losses that can arise with further waste processing.

In this thesis different methodological approaches were followed to answer the various research questions.

The data used for Al from MSW were of different quality. Waste analyses and licensed quantities focus primarily on Al packaging, while Al in composite foils and in Al non-packaging has been only marginally researched. This caused great uncertainties of Al quantities in MSW. Therefore, a characterization of the data uncertainty was performed to evaluate the robustness of the Al flows and the model results. Little attention is generally paid to material quality and thickness, which made it difficult to ascribe losses during waste treatment to insufficient recovery due to particle size or oxidation rates. A more specific investigation and reporting of the quantities and qualities of Al seems advisable.

The survey on the management of Al packaging within European Member States showed lots of inconsistencies and shortcomings of data, which was based on official statistics and from waste management authorities. A direct comparison of the recycling rates within the EU Member States was therefore problematic as e.g. data were often differently or incorrectly assigned, incomplete or rely on differing estimations and assumptions. A clearer assignment of the corresponding data and a more comprehensive reporting obligation on losses and shares of non-packaging, imported and exported waste is necessary

In the scenario analyses for increased recycling rates for Al packaging the results depend, both in terms of recycling rates and net costs, on a large number of dependent variables. In order to be able to statistically assess the relationship between input (independent) and output (dependent) values, a multiple linear regression analysis, using a Monte Carlo simulation, was carried out as part of a sensitivity analysis. In addition, it was examined how the net costs of the different scenarios change with a variation in the input parameters up to +/- 30% of the initial value. This does not eliminate the uncertainty of the data, but it does allow reliable assumptions about the order of magnitude and comparability of the scenarios.

All the studies carried out depend heavily on the availability, quality and scope of the data. In general, it has been shown that the completeness and quality of data needs to be improved if there is interest in improving reliable and more robust results about the circularity of Aluminum in particular and materials in general. It should also be noted that the reported recycling rates appear to be higher than the quantities of Al actually recycled, due to the aforementioned inadequacy of data allocation.

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8. List of Figures

9. List of Tables

10. Appendix (Paper 1-3)

Waste Management 76 (2018) 217–224

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Country report

Current status of circularity for aluminum from household waste in Austria

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A B S T R A C T

Aluminum (Al) represents the metal with the highest consumption growth in the last few decades. Beside its increasing usage in the transport (lightweight construction of vehicles) and building sector, Al is used ever more frequently for household goods like packaging material, which represents a readily available source for secondary aluminum due to its short lifetime.

The present paper investigates the extent to which this potential source for recycling of Al is already utilized in Austria and highlights areas for future improvements. Thereto a detailed material flow analysis for Al used in packaging & household non-packaging in 2013 was conducted. In practice, all Al flows starting from market entrance through waste collection and processing until its final recycling or disposal have been investigated. The results indicate that about 25,100 t/a (2.96 kg/cap/a) of Al packaging & household non-packaging arose as waste. At present about 9800 t/a, or 39%, are recycled as secondary Al, of which 26% is regained from separate collection and sorting, 8% from bottom ash and 5% from mechanical treatment. The type of Al packaging & household non-packaging affects the recycling rate: 82% of the total recycled quantities come from rigid packaging & household non-packaging, while only 3% of the total recycled Al derives from flexible materials. A significant amount of Al was lost during thermal waste treatment due to oxidation (10%) and insufficient recovery of Al from both waste incineration bottom ash and municipal solid waste treated in mechanical biological treatment plants (49%). Overall it can be concluded that once Al ends up in commingled waste the recovery of Al becomes less likely and its material quality is reduced. Although Austria can refer to a highly developed recycling system, the Austrian packaging industry, collection and recovery systems and waste management need to increase their efforts to comply with future recycling targets.

1. Introduction

The world's population keeps growing, and so does its demand for goods of all kinds. The increasing fear of shortage or unavailability of raw materials from natural sources and the unanswered questions of how to handle the severe impacts on the environment from incessant production are huge challenges in the 21st century (RLI, 2015). The scarcity of raw materials is especially delicate in countries (and communities like the European Union) which are highly dependent on imports of commodities (OECD, 2015).

Changing the way of use from a linear to a more integrated pattern, where the consumption of raw materials is reduced and the re-use of existing goods is encouraged, could be an important step towards meeting these challenges (EEA, 2016). Such an integrated pattern is the essence of the concept of the Circular Economy. While there is no uniform definition of Circular Economy, all do have the same bottom-line: "the objective of the circular economy is to preserve the value of utilized resources and materials as long as possible, to use them as frequently as possible, and to produce as little waste as possible (ideally none at all)" (Wilts, 2016). The European Environment Agency EAA (2016) adds that Circular Economy has "a positive, solutions-based perspective for achieving economic development within increasing environmental constraints". The European Commission has introduced an ambitious "EU Action Plan for the Circular Economy" and has released various legislative proposals like the "Proposed Directive on Packaging and Packaging Waste", which demands that 65% of all packaging waste should be reused and recycled by the end of 2025, resp. 75% by 2030 (EC, 2015).

The packaging sector in Austria produces around 1.3 million t of packaging waste p.a., which is equivalent to more than 30% of Municipal Solid Waste (MSW) generation (BMLFUW, 2017), while contributing only 1% to the gross national product (PROPAK, 2017).

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One of the frequently used packaging materials is Al, due to its versatility and outstanding properties. It serves as a barrier against light, fluids, oxygen, microorganisms and other substances, prevents flavor or scent impairments, and ensures durability. Packaging usually has short life cycles and therefore requires constant reproduction of packaging materials.

In order to gain primary aluminum, the raw material has to be extracted from Bauxite in an energy-intensive process. Using secondary instead of primary raw material through recycled and re-melted Aluminum scrap can reduce the energy input by 90–95%. The mining of Bauxite also has severe impacts on the local and global ecology because large extraction areas are situated in tropical rainforests and the red mud that remains can lead to environmental damage. Furthermore, dependency on imports, price volatilities and insecurities of supply caused by geopolitical factors have to be considered (Rüttinger et al., 2016; Wilts, 2016).

The environmental, political and economic impacts associated with the production of Al packaging could promote the use of secondary Al, which requires that recycling be optimized and losses in the recycling chain minimized (Aludium, 2017; Bühler, 2017). The minimum targets for reuse and recycling with respect to Al contained in packaging waste stipulated in the "Proposed Directive on Packaging and Packaging Waste" are set at 75% by the end of 2025 and 85% by the end of 2030 (EC, 2015). For Austria this also requires an adjustment to the Austrian Packaging Ordinance 2014 (Verpackungsverordnung, VVO), which specifies a minimum recycling rate of only 50% for metals (Republik Österreich, 2014). The Al balance for packaging applied in this study differs from official surveys because it includes all Al used as packaging material and therefore expands the usually licensed Al packaging quantities applied, which consider only packaging containing more than 80% Al.

This paper aims to analyze the current status of Al management for Al packaging & household non-packaging in Austria and to identity potentials for improvement with respect to the implementation of a circular economy, as required by the European Commission. Austria was chosen as a case study.

2. Material and methods

In this study the method of Material Flow Analysis (MFA) is used to capture, describe and investigate the physical flows (Brunner and Rechberger, 2017) of Al packaging & household non-packaging in Austria for 2013. The material flow model pre-sented delineates the different stages of waste management (col-lection, sorting, treatment and disposal) and the recycling process itself (re-melting) (Fig. 1). In practice, the following pro-cesses are considered:

- Household Al packaging & non-packaging consumption
- Waste collection and sorting
- Incineration and bottom ash treatment
- Mechanical treatment
- Industrial incineration (cement industry)
- Aluminum smelter (melting plant)
- Al losses
- Landfill.

Al in packaging & non-packaging was subdivided into three product groups: rigid, semi-rigid and flexible (López et al., 2015). The allocation to these categories is based on a survey of a product-related substance flow analysis (ProSFA) for residual waste (RW) in Vienna by Taverna et al. (2010). The wall thickness of Al (Table 1) as defining element strongly influences the behavior of Al during waste treatment (e.g., oxidation during combustion, separability via eddy current separator) and affects also the recovery yield of Al scrap in the melting plant (e.g. higher losses for flexible Al).

2.1. System description and data collection

All data refer to the year 2013. If no data were available, reference data from different times were used and associated with a degree of uncertainty (see Section 2.2).

For packaging Al, it was assumed that waste generation equals the market volume of packaging as it is generally disposed of shortly after use and any stocks of packaging can hence be neglected. In contrast, the lifetime of non-packaging is much longer and varies by product. In this study, the lifespan of non-packaging as well as its stock buildup was disregarded. Only the annual quantities of discarded non-packaging goods from households into MSW were considered. The determined recycling rate of Al refers to all Al (packaging and household non-packaging) present in MSW.

2.1.1. Market volume and waste generation

The input flows F1.01–F1.06 describe the amount of Al packaging & household non-packaging used in Austria in 2013. Different products were distinguished (beverage cans, beverage cartons, composite foils and other packaging & household non-packaging).

The market volume of packaging and waste quantities of household non-packaging was calculated from data of Austria's leading packaging compliance scheme Altstoff Recycling Austria (ARA, 2017), a survey on packaging by Hauer et al. (2015) and various waste analyses. The market volume of beverage cans (F1.01) and beverage cartons (F1.02) were based on market volume and collected quantities (ARA, 2017; Hauer et al., 2015). Beverage cartons partially contain Al foil (ARGE Hauer, 2016), whereby an average Al content of 4% was assumed (Fachverband Kartonverpackungen, 2017).

The market volume of Al composite foils was difficult to identify because no specific data were available. This is mainly due to the fact that the material share of Al has to be above 80%, otherwise it is classified as composite material and is not officially allocated to Al packaging because the dominant material is mostly plastic or paper (ARA, 2015). For the Al balance conducted, however, all Al used in composite material was relevant and thus included in the mass balance. The market volume of Al in composite foil (F1.03) was estimated based on the ProSFA study for residual waste (RW) in Vienna by Taverna et al. (2010). These data were compared with a Spanish study by López et al. (2015) and esti-mates from the European Aluminium Association (EAA, 2017) and the European Aluminium Foil Association (EAFA, 2017).

Other Al packaging (F1.04) include Al packaging except beverage cans, foils in beverage cartons and composite foils. Data about their usage in Austria were obtained by a market survey and waste analyses conducted by Hauer et al. (2015).

Al household non-packaging comprises household foil and other non-packaging items such as household wares, fittings, tubes, coins, or coffee capsules. The amount of household foil (F1.05) was based on a market analysis from Hauer et al. (2015). The volume of other Al household non-packaging (F1.06) was dif-ficult to assess and could only be estimated via various sorting analysis (Amt der Kärntner Landesregierung (Ed.), 2012; AARGE Abfallanalyse Oberösterreich 2013, 2014; HARGE Hauer, 2016; Boku, 2011; Hauer et al., 2015; Hauer and FHA, 2010; IUT and SDAG, 2014; Land Salzburg, 2013; Salzmann Ingenieurbüro, 2000).

2.1.2. Collection and sorting

After usage, Al packaging & household non-packaging enter separate collection & sorting systems (F2.01) or end up as RW (F2.02) or occasionally as bulky waste (BW) (F2.03). Littering

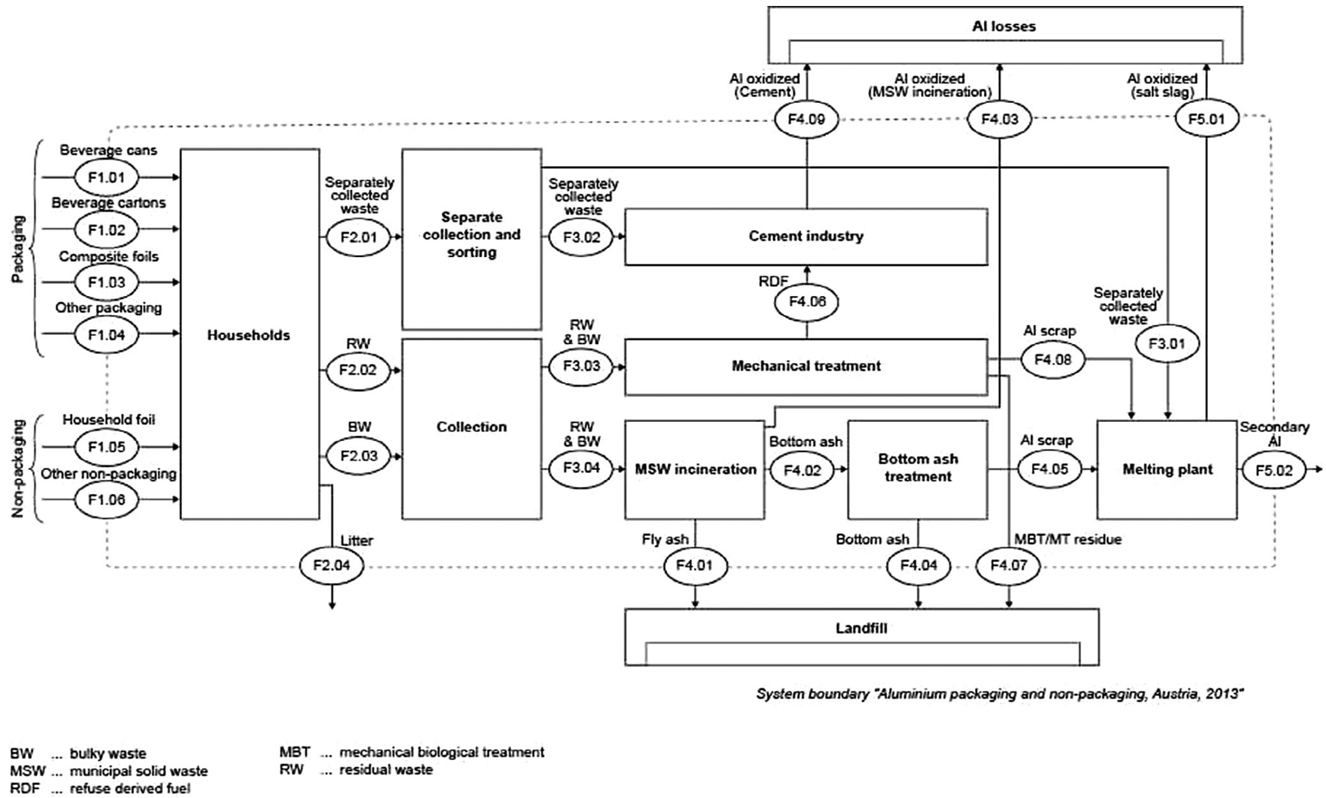

Fig. 1. Model overview for Al packaging & household non-packaging management.

Table 1
Al in packaging & non-packaging divided by product groups.

Product group	Wall thickness	Packaging	Non-packaging
Rigid	>0.2 mm	Beverage and food cans, aerosol containers, etc.	Household ware, fittings, coins, kitchen appliance, etc.
Semi-rigid	0.05–0.2 mm	Closures, tubes, trays, etc.	Freezer containers, tubes or hosts, etc.
Flexible	<0.05 mm	Foil and laminated foil (composite or mono material, e.g. butter or chocolate wrapping)	Household foil, coffee capsules, etc.

(F2.04) was neglected because intensive and regularly repeated clean-up work by municipalities (Loimayr, 2010) and retained solids at the power stations of Austrian rivers complement common waste collection systems and prevent dissipative losses (Verbund, 2017). The separately collected and sorted Al packaging & household non-packaging, except for beverage cartons and separately collected composite foils (F3.02), are provided as Al scrap to Al smelters (F3.01).

2.1.3. Waste treatment

Al packaging & household non-packaging, which is not separately collected, ends up in RW & BW. Both wastes are sent for further processing, where they undergo thermal (F3.04, 73%) or mechanical treatment (F3.03, 27%) (BMLFUW, 2014, 2015).

2.1.3.1. Mechanical treatment. During mechanical treatment Al is recovered as Al scrap via eddy current separators (F4.08).

According to MFAs by Skutan and Rechberger (2007), it is estimated that about 25% of the non-recovered Al generated by mechanical-biological and mechanical treatment (MBT/MT) plants goes to landfills (F4.07). Around 75% of the non-recovered Al ends up in the cement industry, where it contributes as refuse-derived fuel (RDF) to the clinker generation (F4.06); the Al contained therein is lost for Al recovery (F4.09).

Within Austria fourteen MBT/MT plants with a treatment capacity of around 660,000 t (BMLFUW, 2017) process municipal and commercial waste (CW). For the recovery of Al as Al scrap (F4.08), information was obtained by the operators of MBT/MT plants and a survey conducted by the Federal Environmental Agency of Austria (Neubauer and Öhlinger, 2008). As operators' data were only partially available, the given data (79% of all MBT plants with respect to waste capacities) were used to determine an average Al recovery rate for Austrian MBT/MT plants, which was 2.8 kg Al recovery per ton of RW & BW input (Table S1 in the supplementary material). This recovery rate was subsequently used in conjunction with the waste quantities processed to determine the absolute Al recovery quantities.

2.1.3.2. MSW incineration and bottom ash treatment. During the combustion process in municipal solid waste incineration (MSWI), Al is partly transferred into fly ash, whereof <0.5% of the fly ash is of metallic Al (F4.01) and 2% of oxidized Al (F4.03) (Wien Energie, 2012), while the residual metallic Al remains in the bottom ash (BA) (F4.02).

Al melts during incineration (850 °C) at around 660 °C and forms Al oxide (Al_2O_3) through the reaction with oxygen. The con-version from Al oxide to Al is economically unfeasible and oxidized Al is considered a loss (F4.03). The level of oxidation of Al packag-ing & household non-packaging materials in combustion and re-melting processes depends on the thickness, mechanical resistance and the Al alloy (Biganzoli et al., 2012). It is difficult to define the degree of oxidation and not many extensive studies addressing this topic have been undertaken (Biganzoli et al., 2012; Hu et al., 2011; López et al., 2015). Biganzoli et al. (2012) realized the most practicable experiments "in a full-scale waste to energy plant during standard operation" and their results are hence the foundation for calculations of oxidation rates in the present study. In particu-lar, the following oxidation rates were applied to determine the losses of Al packaging & household non-packaging during the combustion process (F4.03): 9.2% for rigid, 17.4% for semi-rigid and 58.8% for flexible material.

All non-combustibles remain in the BA and undergo further treatment. The amount of metallic Al present in the BA (F4.02) was determined as the difference between the amounts of Al inserted into waste incineration (F3.04), on the one hand, and the amount of Al oxidized during combustion (F4.03) and Al pre-sent in fly ash (F4.01), on the other hand. For the latter (amount of the Al removed via fly ash), the information provided by the big-gest operator of waste incineration plants in Austria was used (Wien Energie, 2012). The amount of the oxidized Al was estimated on the given oxidation rates by Biganzoli et al. (2012) and the pro-portional distribution of rigid, semi-rigid and flexible products.

After ferrous metals have been removed, non-ferrous metals (NFe) are separated from the BA by eddy current separators (ECS) and the Al scrap obtained can be re-melted (F4.05). The recovery of Al from BA treatment from MSWI depends on the technology available and/or used.

In Austria there are eleven incineration plants for MSW with a total annual processing capacity of 2.5 million t (BMLFUW, 2017). There are significant differences in the recovery of NFe and Al recovery from BA treatment. Some plants do not recover NFe at all, whereas other plants mechanically pre-treat their waste before combustion, but only one of these upstream systems sepa-rates NFe. Detailed information on specific recovery volumes from different MSWI plants in Austria are provided in the supplementary information. Data from MSWI were only partly available and many incineration plants have heterogeneous waste inputs with significant amounts of commercial and industrial waste. The four waste incineration plants in Vienna burn nearly exclusively RW and maintain precise data recording. Furthermore, the processing of the BA from these plants, using up to three eddy current separa-tors and sieving down to a grain size of 7–8 mm (Prisching, 2017), can be regarded as typical for Austrian waste incinerators. Hence, the corresponding Al recovery (kg Al recovered per ton of residual waste incinerated) served as a reference value for waste incineration and bottom ash treatment in Austria (Stadt Wien, 2017). This reference value and data about the amount of RW & BW incinerated were used to assess the overall amount of Al packaging and household non-packaging recovered as Al scrap from BA (F4.05). The Al recovery from the BA from MSWI was 1.7 kg per ton of RW & BW input (Table S1 in the supplementary material). The losses of metallic Al (F4.04) via the landfilling of the bottom ash was calculated by balancing the process "bottom ash treatment".

2.1.4. Al recycling

The recovered Al scrap from collected packaging & household non-packaging (F3.01), MBT/MT treatment (F4.08) and bottom ash (F4.05) is fed into melting plants. During the re-melting pro-cess, minor losses of Al occur due to further oxidation (F5.01). It is worth noting that Al scrap is seldom free of adhesions, moisture or impurities, which may decrease the yield during the re-melting process. For the present study, information about the Al losses during re-melting were provided by the largest Austrian producer of secondary Al (Fragner, 2017) and estimated at 3%. The Al regained from the re-melting process is fed back into the Al system as secondary Al (F5.02) and reflects the physically recycled volume of Al.

The MFA model displays all Al oxidation losses as export flows. In reality, however, these flows end up in landfills or final products (e.g. cement), which was not shown in the figure for the sake of clarity.

2.2. MFA and data characterization

The data on material flows in this study are based on various data sources, which again are based on different reporting methods. If no information was given, missing data were complemented from scientific investigations or, if needed, using data from similar processes. A characterization of the data uncertainty was conducted in order to evaluate the robustness of the Al flows and model results. For the quantitative data, mean values and uncer-tainties (given by the standard deviation) were calculated, whereby for the latter a normal distribution was assumed. To eval-uate the data and assess the resulting uncertainties, a rating scheme with assigned coefficients for various indicators, intro-duced by Laner et al. (2016), had been applied. Their approach goes back to a data quality assessment scheme introduced by Weidema and Wesnæs (1996) and a data uncertainty assessment of material flows using data classification from Hedbrant and Sörme (2001). In practice five data quality indicators (reliability, completeness, tem-poral correlation, geographical correlation and other correlations) were rated on a scoring system from 1 to 4, with 1 ranking the highest (good data quality) and 4 the lowest (poor data quality). The indicator reliability refers to the methodology of the data generation and how well the data were documented and verified. Completeness evaluates all relevant mass flows in question and assesses the extensiveness of the data. Temporal and geographical correlations refer to the consistency and deviation of the data in time and space. The other correlation indicates values related to a different product or technology. Sometimes information relies on expert judgements. In such cases the reliability of the expert's opinion is used as the only indicator (Laner et al., 2016). The uncertainties were quantified by coefficients of variation (CV, standard deviation divided by mean), and aggregating the CV's of the individual indicators established the overall uncertainty of the data. A detailed overview of quality indicators, assessment criteria and calculated uncertainties can be found in the supplementary information (Table S3–S6).

The STAN (substance flow analysis) software was chosen to balance the input data of the MFA with respect to uncertainties and inconsistent data. The inherent Sankey diagram (Fig. 2) displays the thickness of the data flows proportional to their value (Cencic and Rechberger, 2008).

3. Results

The results of the MFA are presented in Fig. 2. The market volume of Al packaging & household non-packaging was estimated at 25,100 ± 2120 t (2.96 kg/cap/a) according to surveys on packaging volume in Austria 2013 and RW analyses of Al non-packaging. This figure was made up of 17,700 ± 670 t (2.09 kg/cap/a) of Al found in RW & BW (F2.02 & F2.03) plus 7400 ± 800 t (0.87 kg/cap/a) of separately collected Al (F2.01). The main use (45%) of Al in households was for beverage cans. Significant differences were found between the market volume (11,300 ± 250 t) and the collected volume of beverage cans (via separate and commingled waste collection), amounting to 800 ± 210 t. It was assumed that these missing quantities were also separately collected and sorted, but not included in official statistics as these quantities were managed largely by scrap traders (not displayed in Fig. 2).

1600 ± 920 t of Al foil was used in composite packaging material (1300 ± 910 t Al foil in composite material and 350 ± 150 t in beverage cartons). The part of Al foil in composites that was collected separately (600 ± 80 t) was sorted out and lost as these quantities

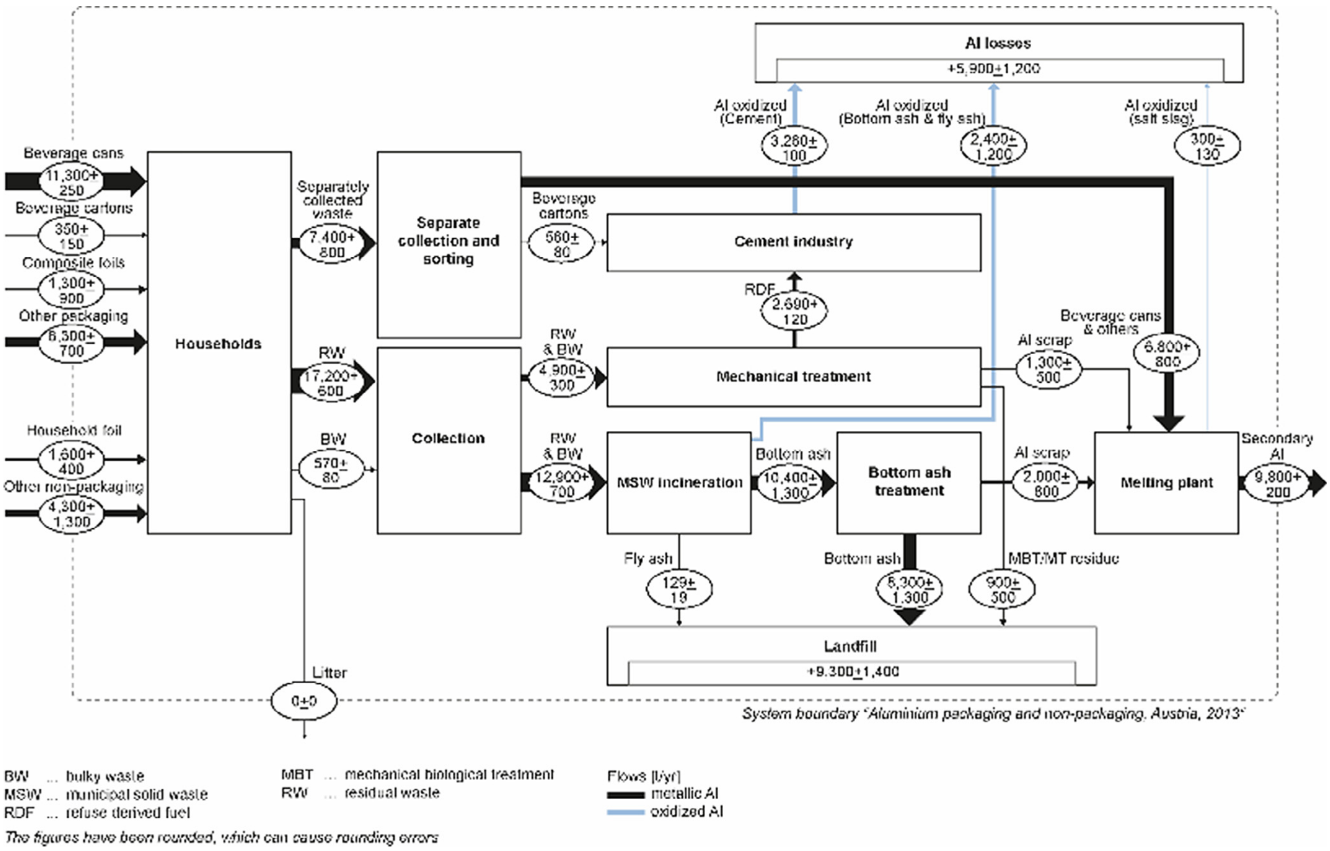

Fig. 2. MFA results. Al packaging & non-packaging from households.

are not recyclable and are sent into industrial incineration. There Al oxidizes and finally ends up as Aluminum oxide in cement.

The remaining packaging & household non-packaging quantities (F1.04, F1.05 and F1.06) arose from other Al packaging (630 0 ± 670 t, all products but beverage cans and foils) and household non-packaging (5900 ± 1.340 t), of which 1600 ± 400 t were household foil.

The Al in RW & BW was further processed, after which 3300 ± 890 t of Al was recovered as Al scrap. The main share came from BA treatment (2000 ± 760 t), while the recovery per t waste input from MBT/MT is significantly higher (2.85 kg Al per t waste input) than from MSWI with subsequent BA treatment (1.74 kg Al per t waste input). These higher recovery rates for MBT/MT plant might be explained by the fact that a significant amount of Al oxidizes during incineration and is thus not available for metal recovery. The recovered Al from waste processing (MBT/MT and BA treat-ment) and separate collecting and sorting Al is remelted (10,100± 1220 t) and largely regained as secondary Al. Only minor amounts of Al (300 ± 130 t) are lost in the melting plant.

Overall, about 39% ± 4.8% (9800 t ± 1190 t) of the Al present in packaging & household non-packaging are currently recycled and utilized as secondary Al, of which 26% is regained from separate collection and sorting (6600 ± 800 t), 8% from BA (2000 ± 760 t) and 5% from MBT/MT treatment (1200 ± 470 t). The main losses occur through oxidation (2400 t ± 1220 t) during waste combus-tion and owing to insufficient recovery of Al from MSWI bottom ash (8400 ± 1300 t) and RW & BW treated in MBT/MT plants (350 0 t ± 510), as shown in Fig. 3.

The type of Al packaging & household non-packaging has a very considerable influence on the recycling rate: 82% (8100 ± 1700 t) of the total recycled quantities come from rigid packaging & household non-packaging, while only 3% (300 ± 70 t) of the total recycled

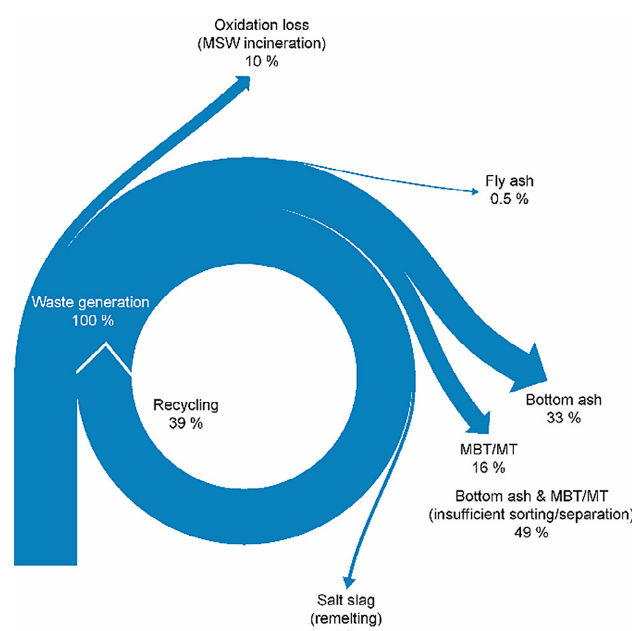

Fig. 3. Circular representation of Al packaging & household non-packaging, Austria 2013 (All flows leaving the circle represent losses of metallic Al. Al losses due to the utilization of RDF in the cement industry are allocated to MBT/MT).

Al derives from flexible materials. The results thus show a positive correlation between recycling rates and increasing thickness of the Al material utilized: 46% of rigid and 38% of semi-rigid, but only 9% of the flexible Al material is recycled (Fig. 4). The main losses occur

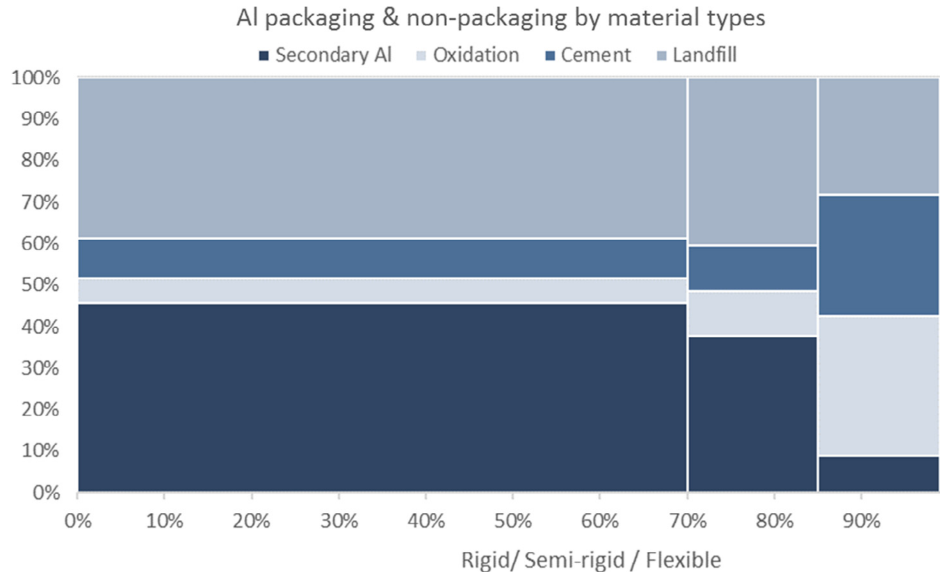

Fig. 4. Recycling & losses of Al packaging & household non-packaging, Austria 2013.

for rigid (6200 t ± 1350 t) and semi-rigid (1400 t ± 300 t) material during BA treatment (64%, resp. 58%), while the main factor for losses of flexible Al materials is oxidation (37%).

Detailed information about the material flows of Al packaging & household non-packaging at the level of product groups is presented in Fig. 5, while concrete numbers are outlined in the supplementary (Table S2). Besides the fact that thicker Al products are more likely to be recycled, the figure also highlights that 11% of the total Al (2700 ± 1230 t) ends up as oxide in the cement indus-try. There Al oxide is of use for the final product cement, whose typical Al_2O_3 content varies between 4 and 8%. Considering an average content of Al oxide in clay of 16% (raw material and most important Al carrier for the cement production), the "unwanted" utilization of Al packaging & household non-packaging in the cement industries may substitute almost 40,000 t of clay per year (Schneider et al., 2011).

For the present study, this "alternative" utilization of Al, however, has not been accounted for the recycling rate as only the recovery of metallic Al was considered. This is not only in line with official waste statistics, but is also justified by the fact that the huge energy amount embedded in metallic Al, which is one of the major reasons for Al recycling, is lost during utilization in the cement industry.

4. Discussion and conclusions

As this work showed, around 25,100 t of Al from packaging & household non-packaging have been used in Austria in 2013, whereof 9800 t (39%) of the Al returns as secondary Al into circulation. Separately collected Al (67%), especially beverage cans, contribute the most. The main losses of Al occur through oxidation (11%) during incineration and because of limited recovery from subsequent processes or other sorting constraints (49%).

The material thickness plays an important role for Al recovery. Thicker material as used in rigid and semi-rigid products shows

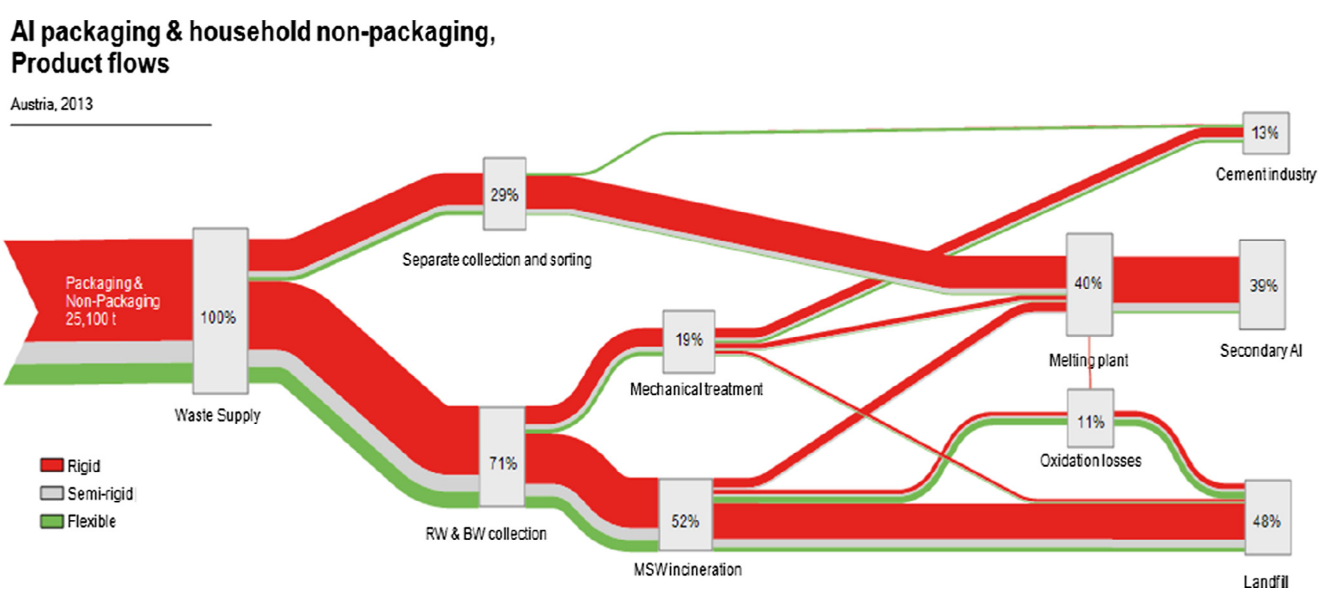

Fig. 5. Material flows of Al packaging & household non-packaging at the level of the product groups rigid, semi-rigid and flexible.

higher collection and sorting rates, resp. recovery rates from waste processing. The latter is caused by lower oxidation rates and losses from MSWI BA and MBT/MT treatment (Figs. 4 and 5).

Investments in better separation technologies (NFe separation from BA and MBT/MT) appear indispensable to obtaining a significant increase in the recycling rate of Al. The current technology in Austria allows detecting and recovering Al lumps larger than 3–4 mm, while smaller ones remain in the residuals. Only very powerful ECS are able to separate significant amounts of Al from the fine fraction (0–6 mm) of bottom ash (Fuchs and Schmidt, 2013), which contains 40–60% of the total Al present in the BA (Allegrini et al., 2014; Berkhout et al., 2011; Biganzoli et al., 2013; Hauer, 2010; Mitterbauer et al., 2009; Steketee and Oudenhoven, 2011; Xia et al., 2016). Very fine grained Al (<2 mm) is often encapsulated by mineral lumps or metallic agglomerations and is thus not recoverable from BA (Breitenstein et al., 2015). The small grained Al fractions "can cause problems, particularly for use in cement bound materials where [...] aluminum can lead to the generation of hydrogen leading to swelling and a decrease in the mechanical properties of the structure." (ISWA, 2015). Even if those small-grained Al particles could technically be removed in order to avoid problems with a subsequent utilization of bottom ash as construction material, utilization of these Al fractions is highly questionable as particles <1 mm generally fully oxidize and find little use in smelters. Therefore other potential uses need to be developed (Biganzoli, 2013).

Overall, once Al is not collected separately and enters subsequent waste treatment processes, its recovery becomes less likely and its material quality is reduced.

It should be noted that the figures given are not comparable to official statistics for Al packaging recycling rates in Austria as different products (Al composite foils and Al non-packaging products are included) and different points of measurement are considered. Official statistics use data on the input into recycling facilities, whereas in this study outputs of the Al smelters were presented.

Nevertheless, the results clearly demonstrate that although Austria already has a highly developed recycling system in place (also compared to other EU countries), greater efforts by the Austrian packaging industry, in the collection and recovery systems and in waste management need to be made on the way to a Circular Economy to reach the ambitious objectives of 75% for 2025, resp. 85% for 2030 regarding the reuse and recycling of Al contained in packaging waste.

The data used in this work were of variable quality. Waste analyses and licensed quantities focus primarily on Al packaging, while Al in composite foils and in non-packaging has been only marginally researched. This caused great uncertainties of Al quantities in MSW. Little attention is generally paid to material quality and thickness, which made it difficult to ascribe losses during waste treatment to insufficient recovery due to particle size or oxidation rates. Further studies might also look into different yields based on Al qualities from separate collection and sorting mechanisms as well as from mechanical and BA treatments.

For better recycling of Al from packaging & household non-packaging, more specific research on Al quantities and qualities seems recommendable.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2018.02.034.

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Management of aluminium packaging waste in selected European countries

R Warrings and J Fellner

Abstract

By the end of 2025, a minimum of 50% of aluminium packaging waste has to be recycled within the Member States of the European Union. Aluminium packaging can be recovered through different systems (separate collection, deposit refund systems, informal collection, treatment of municipal solid waste incineration bottom ash or mechanical treatment of mixed municipal solid waste). The present article analysed if the agreed targets for the recycling and reuse of aluminium packaging are reasonable and realistic. To this end, the management of aluminium packaging in 16 selected European countries, yielding results for 11 countries, were investigated. The results show that six out of 11 countries recycle at least two-thirds of the aluminium packaging from MSW and only two report very low recycling rates of 20%. The overall recycling rate reported by the different countries cannot be directly linked to the system of recovery. Only the assertion that a deposit refund system together with selective collection leads to a higher overall collection rate seems permissible. This does not necessarily lead to a higher recycling rate as other countries with similarly high recycling rates make up for it with high amounts of aluminium recovered from bottom ash treatment. A direct comparison of the recycling rates within the European Union Member States, however, is problematic for several reasons, such as data that are often differently or incorrectly assigned, incomplete or rely on estimations and assumptions. The authors therefore propose a clearer assignment of the corresponding data and more extensive mandatory reporting on losses and shares of non-packaging, imported and exported waste.

Keywords

Recycling, aluminium packaging, circular economy, EU member states, municipal solid waste

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Introduction

Municipal solid waste (MSW) is an important 'by-product' of the rising standard of living, and population growth and urbanisation leads to a progressive rise in waste (Hoornweg et al., 2013). The Member States of the European Union (EU) generated 241 million tonnes or 476 kg per capita of household waste in 2014, which was about 8.3% of the total generated waste in the EU-28 (Eurostat, 2017).

In Europe and most countries around the world, recycling is an important factor in dealing with the ever-increasing consumption of resources and waste generation. High recycling rates seem to be achievable in many countries and increase the pressure on others to obtain similarly good results. The Swedish Institute (2018) states that in Sweden 'more than 99% of all household waste is recycled in one way or another' (which is misleading because the included energy recovery is wrongly attributed to the recycling rates) and stakeholders from the industry praise the high re-usability of their materials, including for example the European Aluminium Association (2017), which claims that in several European countries more than 95% of aluminium cans are recycled.

Recycling is an important economic branch as manufacturers, for example, must pay a license fee (extended producer responsibility (EPR)) for the marketed packaging, and waste treatment companies generate revenues from the recovered recyclables (Pires et al., 2011). Preparation for re-use and recycling of waste are key components of modern waste management systems next to waste prevention within the waste hierarchy of the EU (EC, 2008). Recycling does not include energy recovery (with the exception of biodegradable waste), such as waste-to-energy (WtE) from MSW incineration (MSWI) and reprocessing into materials that are used as fuel (EC, 2011). A recycling rate is understood as the ratio of the amount of aluminium packaging that is separately collected or recovered from bottom ash (BA) or by waste processing such as mechanical treatment (MT) and the amount of aluminium packaging brought on the market. Recycling, at least for material fractions paper, glass, steel and aluminium, is considered to be superior to MSWI for environmental reasons (Merrild et al., 2012). Although both technologies, recycling and MSWI, can be

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mutually complementary, they are often considered to be in competition with each other (OECD, 2013; Rand et al., 1999).

In any case, the Member States of the EU have come to the understanding that priority should be given to the reuse and recycling of materials and have consequently established corresponding demands in legislative frameworks for the handling of waste in the EU (EC, 2017). While the recycling targets seemed well defined for the EU Member States, legislative stipulations have left room for interpretation on how to measure the recycling volumes and allowed Member States to maximise recycling rates for their country as much as possible (Eunomia, 2014). This approach was deliberately chosen not with competition between the states for the highest recycling rates in mind, but to provide instead an incentive to improve achievable numbers over time (Kremser, 2017). At the same time, however, the comparability of data on recycling has proven to be difficult. With the approval of amendments on directives for reuse, recycling and landfilling within the Circular Economy Package (CEP) of the EU, the definitions, reporting obligations and calculation methods for the targets have been unified (EU, 2016) and the recycling goals have become more ambitious than before.

The amendments made to Directive 2008/98/EC on waste and the Directive 94/62/EC on packaging and packaging waste demand higher recycling rates, a minimum of 55% of MSW and 65% of all packaging waste by the end of 2025. Regarding the specific materials contained in packaging waste, 50% of plastic, 25% of wood, 70% of ferrous metals (iron), 50% of aluminium, 70% of glass and 75% of paper and cardboard must be recycled by 2025 (EC, 2018). The original European Commission proposal for aluminium was 75% by the end of 2025 (EC, 2015a). Up to now there has been no obligation within the EU to separately report recycling rates for iron and aluminium packaging, but only a reporting obligation for 50% of overall recycling for metal packaging (EC, 2004). Nevertheless, some Member States have already been publishing data on waste and recycling quantities of iron and aluminium packaging to Eurostat for several years.

The present article, by using the example of aluminium packaging, examined whether the agreed targets for the recycling and reuse of aluminium packaging are reasonable and realistic. Furthermore, the study aimed to analyse which recovery strategy or system (separate collection, deposit refund systems (DRS), informal collection, bottom ash (BA) treatment or mechanical treatment (MT) of mixed municipal solid waste (MMSW)) seems most promising in reaching targets, as well as what the respective performance in the different countries is. The correlation between the recovery quantities from the various systems and the overall recycling rate might allow instructive conclusions about potential vulnerabilities in meeting recycling targets and help to generate proposals to attain increased recycling rates.

It was not the purpose of this work to question the reliability of the data obtained. Rather, the differences in official data and the consequent need for a uniform and precisely formulated requirement for data collection should be demonstrated.

Material and methods

Data collection

The data used came from official statistics and from waste management authorities that were either publicly available through Eurostat or national statistics or submitted to the authors upon request. Data from waste treatment companies were omitted because, as mentioned above, the purpose of this work was not to call into question the information used to calculate the recycling rates.

Every year, Eurostat publishes data on the amounts of MSW and metal packaging generated and the material and energy recovery rates provided by the individual Member States of the EU, but no specific data are given by which system the recycled amounts were accomplished. Information on aluminium packaging will only be required by the end of 2025, but some EU Member States have already voluntarily published data on aluminium packaging for several years (Eurostat, 2017). The most up-to-date data were available for 2015 and/or 2016, so all subsequent data were related to this period. Next to the country reports to Eurostat, information from various Member States within the EU have been retrieved for market volumes and recycling rates of aluminium packaging. It is assumed that owing to the short lifetime of packaging, the quantity of aluminium packaging placed on the market is equivalent to the disposed-of and returned quantities of aluminium packaging, which is in accordance with statutory regulations (EC, 2018).

This study tried to encompass a large number of countries with different collection and waste treatment systems and strategies in waste processing. The first selection was determined by the countries already reporting data on aluminium packaging to Eurostat (altogether five countries). Subsequently, countries were selected that already follow well-developed waste strategies and publish data accordingly. Furthermore, attempts were made to incorporate the various collection and waste treatment systems in the selection of countries. Therefore, the following EU Member States, as well as Switzerland and Norway, have been selected for further processing, as shown in the list below, including the corresponding data sources.

- Austria (Altstoff Recycling Austria, 2018, personal communication; BAWP, 2018).
- Belgium (Fost Plus, 2018; OVAM, 2018, personal communication; StatBel, 2018).
- Czech Republic (Eurostat, 2017; MZP, 2018, personal communication).
- Denmark (Brancheforeningen Aluminium Danmark, 2018, personal communication; Statbank Denmark, 2018).
- France (ADEME, 2018; CITEO, 2017, personal communication).
- Germany (Duales System Deutschland, 2018, personal communication; DESTATIS, 2017).
- Greece (EOAN, 2017).
- Ireland (Repak Limited, 2018, personal communication).
- Italy (CiAl, 2017; ISPRA, 2017).

- Netherlands (AFV, 2016; StatLine, 2018).
- Norway (RENAS, 2018, personal communication).
- Poland (Rekopol, 2018).
- Portugal (Sociedade Ponto Verde, 2018, personal communication).
- Serbia (University of Novisad, 2018, personal communication).
- Sweden (FTI - Förpacknings & Tidnings Insamlingen, 2018, personal communication; Swedish Environmental Protection Agency, 2018, personal communication; Returpack/Pantamera, 2018, personal communication).
- Switzerland (BAFU, 2017; IGORA, 2018, personal communication).
- United Kingdom (DEFRA, 2017).

Unfortunately, it was not possible to obtain all relevant data from Denmark, Norway, Ireland, Switzerland, Serbia and Poland. Hence, the analysis focused in the end on 11 countries.

Collection & waste treatment systems for aluminium packaging

According to the Eurostat (2017) 'Municipal waste consists of waste collected by or on behalf of municipal authorities and disposed of through waste management systems. Municipal waste consists mainly of waste generated by households, although it also includes similar waste from sources such as shops, offices and public institutions'. This therefore includes the same type of waste as garden and park waste (including cemetery waste) or street sweepings, which are not generated by households.

The aluminium packaging used is generally collected by bring-systems (containers at public places for different fractions), door-to-door collection (containers, bins or bags collected directly at households with regular frequency), a mixture of both and/or DRS (Eunomia, 2011; Seyring et al., 2015). All these systems (besides DRS) collect all types of aluminium packaging (cans, aerosols, trays, taps, etc.) together with other (packaging and often non-packaging) metals. Only two of the countries surveyed have installed a DRS solely for aluminium cans, where a deposit fee is additionally charged at the time of sale. The fee is refunded upon return of the can. A considerable part of aluminium packaging is intentionally or unintentionally disposed of via the MMSW, which is either landfilled or subsequently processed in MSWI and/or in MT plants. For the last two treatment methods, metals are recovered. Eddy current separators are used in BA processing from MSWI as well as in MT plants to separate non-ferrous metals from other waste materials. Recovery from MSW varies across Member States as not only the shares of MSW treated via MT or subsequent BA processing are different, but also the separation aggregates installed, such as the type and number of eddy current separators (Deike et al., 2012; Fuchs & Schmidt, 2013; ISWA, 2015; Jujun et al., 2014). Specific data on waste generation of aluminium packaging and the various waste management treatments can be found in Table S1 in the supporting information (SI), available online. The volumes collected from selective collection or waste processing are usually gross amounts and adhesives, whereas impurities or moisture content are ignored and not deducted (Stadt Wien, 2017, personal communication).

Which collection and waste treatment options are used may vary significantly between the countries. Sometimes only one or two options are applied. Figure 1 summarises collection systems for metal beverage cans within different EU Member States (Eunomia, 2011). There is an informal sector for collection of aluminium in some countries (Huber-Humer et al., 2018), but not much reliable and usable data is available on this.

Results

Recycling of aluminium packaging in selected EU member states

This study examined the management of aluminium packaging in 16 selected European countries, with results for 11 countries. The quantities consumed of aluminium packaging were between 9000 t (Portugal) and 180,000 t (United Kingdom, UK), respectively, between 0.9 kg (Portugal) and 2.7 kg (UK) per capita per year (Figure 2). A correlation between the use of aluminium packaging and gross domestic product (GDP) could not be established. Countries with a lower GDP consume more (Greece 2.0 $kg\,cap^{-1}\,y^{-1}$) or less (Czech Republic 1.3 $kg\,cap^{-1}\,y^{-1}$) than average (1.6 $kg\,cap^{-1}$); the same applies to countries with a higher GDP (Sweden 2.7 $kg\,cap^{-1}\,y^{-1}$) and Germany (1.4 $kg\,cap^{-1}\,y^{-1}$).

The results show that six out of 11 countries recycle at least two-thirds of the aluminium packaging from MSW and only three report very low recycling rates of 20%–35%, as displayed in Figure 3. Germany (88%), the Netherlands (79%), Sweden (77%) and Belgium (76%) achieve very high recycling rates, whereby only Germany, next to Sweden, uses a deposit refund system for aluminium beverage cans. These two countries have the overall highest collection rates (DRS and selective collection), but other countries with similar recycling rates make up for it with high amounts of aluminium recovered from BA treatment.

Hence, based on the available data it can be concluded that countries were able to achieve a high recycling rate for aluminium packaging either through a very high return rate from the separate collection or elaborate processing of MSW (BA treatment and/or MT) (see Figure 4).

Low recycling rates cannot be directly linked to the type of collection and waste treatment. EU studies show that less developed separate collection systems can be associated with low recycling rates (Seyring et al., 2015). Certainly, a generally low recycling rate of aluminium packaging can be correlated to rather high rates of landfilling (50%–84%). On the other hand, the six countries with the highest recycling rates

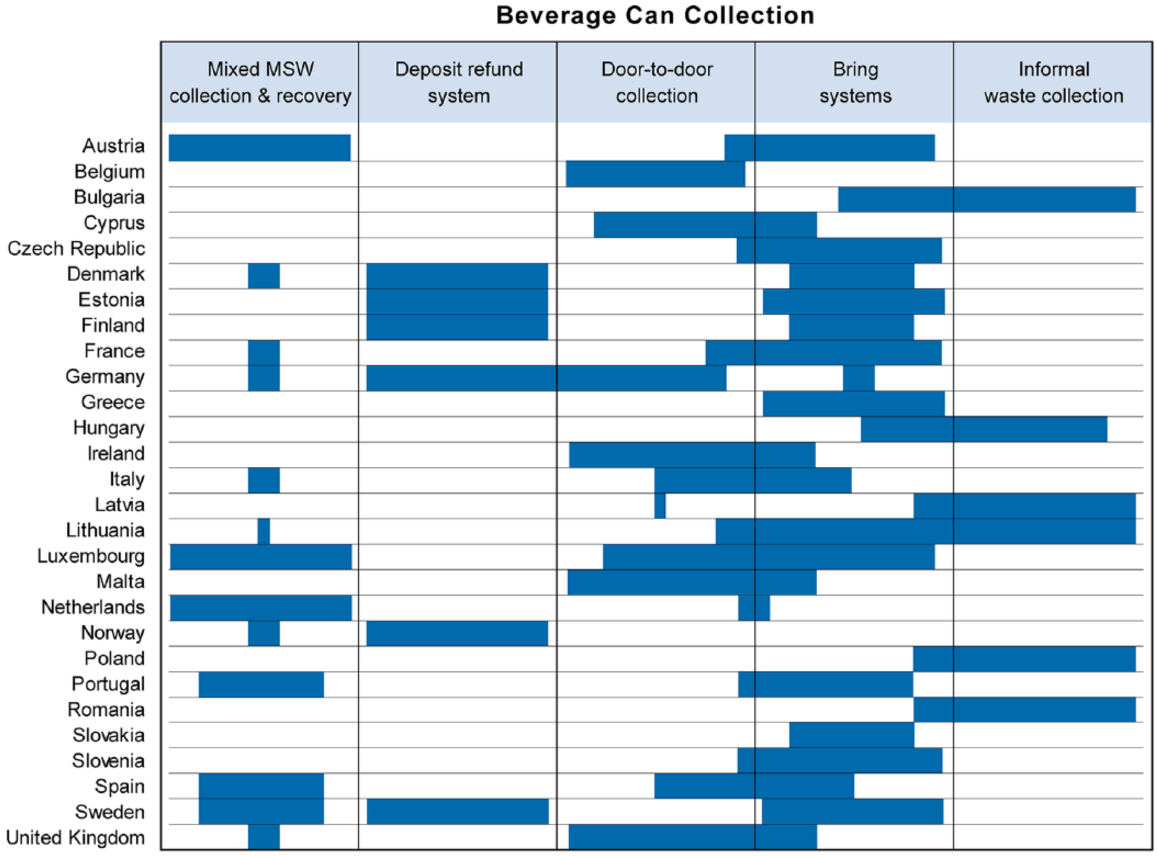

Figure 1. Collection systems for metal beverage cans within EU Member States (modified version based on Eunomia (2011)).

Figure 2. Consumption of aluminium packaging in selected EU Member States (data given in kilograms per aluminium cap y^{-1}).

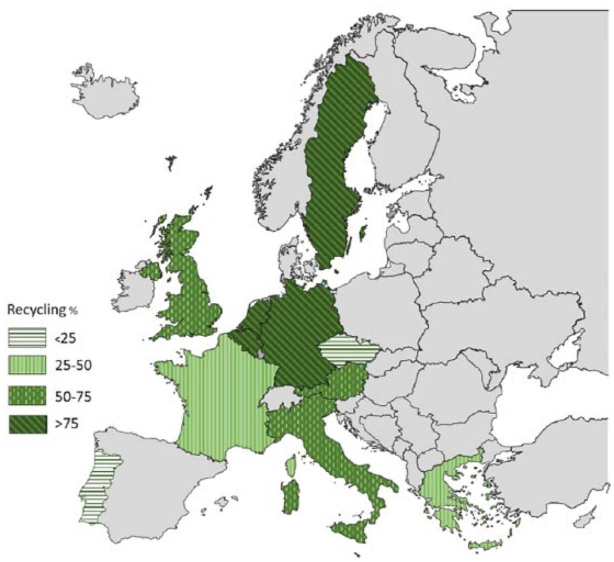

Figure 3. Recycling rates for aluminium packaging in selected EU Member States (in %).

(except Italy) only landfill 1%–3% of their MSW, as Table S1 in the SI indicates.

No overall correlation could be demonstrated between consumption and recycling rates, as for example Germany (1.4 kg cap^{-1}) and Portugal (0.9 kg cap^{-1}) have a low consumption rate, while Germany has a high (88%) and Portugal a low (20%) recycling rate. The UK, on the other hand, has a high consumption rate (2.7 kg cap^{-1}) and a medium recycling rate (51%). However especially in the two countries with the smallest recycling rates (Czech Republic, Portugal), a low per capita consumption (0.9–1.3 kg cap^{-1}) can be observed. The calculation of correlation coefficients was done according to Pearson (see SI, Table S2 and Figure S4).

Inconsistencies and shortcomings of data

A direct comparison of the recycling rates within the EU Member States is, however, problematic for several reasons, as for example data are often differently or incorrectly assigned, incomplete or rely on estimations and assumptions. Hereinafter, a few aspects should be addressed.

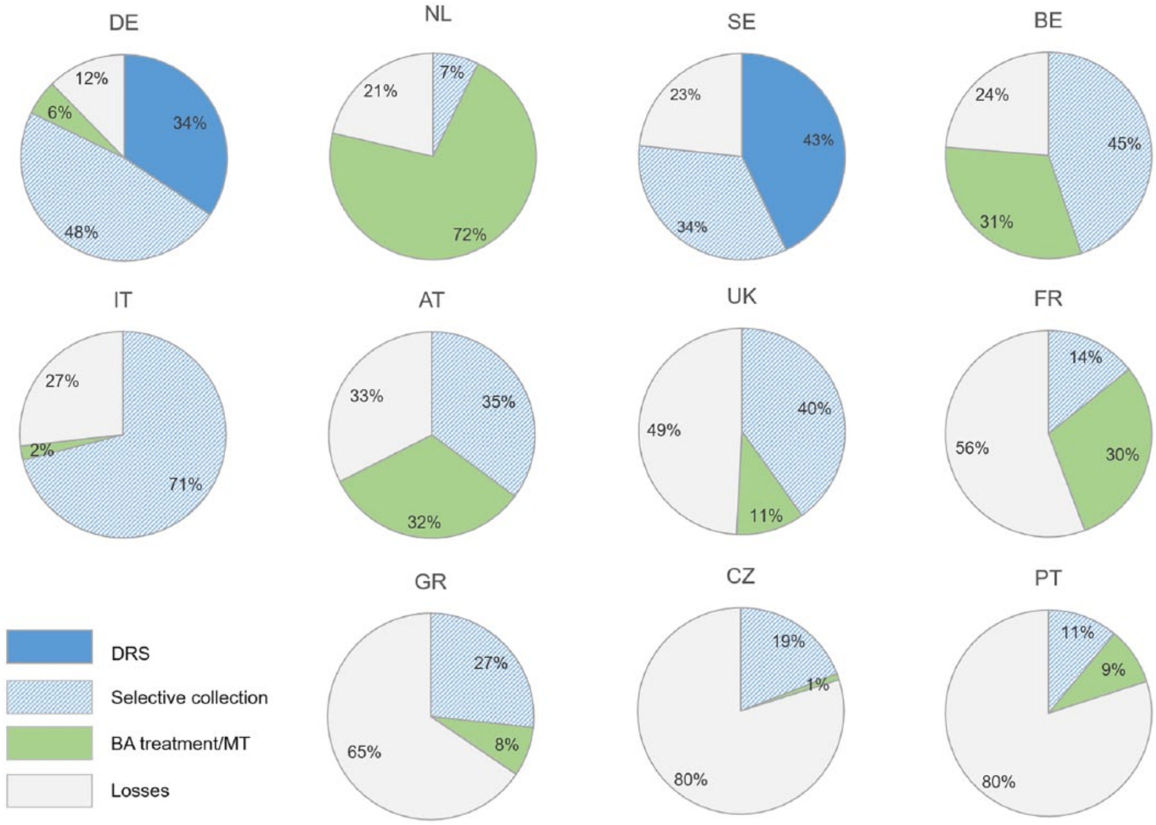

Figure 4. Losses and recovery of aluminium packaging through different systems in selected EU Member States (in %).

Individual countries interpret the somewhat vague definition of MSW (see Chapter 2.2) differently. Some countries consider only waste from households as MSW, whereas other countries also include similar waste types coming from other sources, such as waste from parks and streets, offices or commercial and industrial activities. These waste streams are either added to varying degrees to municipal waste or not, depending on the design of the waste collection system. This can lead to different volumes of MSW generation in the Member States (EEA, 2013), but also to deviant results in national statistics through the different allocation of these waste streams, leading to divergent recycling results.

In some countries, thermal treatment of MSW is widespread and waste incineration capacities are higher than the domestic production of combustible waste. Therefore, considerable quantities of waste are imported into such countries and out of those countries for which it is advantageous to be able to reduce their waste volumes going untreated to landfills. This leads to changed recycling rates both in the exporting country with a lower waste volume and in the importing country with a higher recycling rate (Eunomia, 2011). A report on waste capacities by Wilts and Gries (2015) assume that countries like the UK, Italy, Ireland, France and Finland export MSW to the extent of 'up to 6% of their respective incineration capacities', while other countries (Belgium, Luxembourg and Sweden) need to import waste 'in order to keep their incineration capacities at sufficient utilization rates'. In Austria in 2015 99,000 t of MSW were imported and mechanical (pre)treated or combusted, while 78,000 t were exported (BlgNR. 7840/AB XXV.GP, 2016).

The ability to recover metals from MT or, more frequently, from BA treatment is used by many countries. For the aluminium quantities recovered, it is often assumed that all metals present in the bottom ashes from waste incineration originate from metal packaging, which is false, because the waste fed into incineration plants contains packaging and non-packaging aluminium (OVAM, 2018, personal communication).

The same applies to the assumption that the ashes processed originate exclusively from MSW incinerated. However, most plants also utilise significant quantities of commercial and industrial wastes. In Austria for example, in MSWI plants 2.4 million tonnes of waste was combusted in 2015, of which only around 1.7 million tonnes came from MSW (BAWP, 2018).

It is also important to note that the quantities recovered from BA treatment or MT are often based on estimations of average recovery yields for metals instead of annually achieved actual recovery quantities. Sometimes these yields simply refer to the recovery potential (Schüler, 2017). These estimations are measured differently in each country, depending on particle size and degree of separation. In the Netherlands for example, it is assumed that 77% of non-ferrous metals larger than 5.6 mm are recovered (AFV, 2016), while in Austria 50% recovery of particles larger than 4 mm is assumed (Hauer, 2010).

The input quantities of aluminium packaging within the EU Member States can also vary, because sometimes commercial and industrial packaging is included and sometimes not.

The aluminium quantities recovered are generally gross amounts, which include impurities, adhesives or moisture. The share of these non-related materials often seem to be larger than the legally allowed 10%. This is true for reported quantities from BA/MT treatment (Skutan and Brunner, 2005; Stadt Wien, 2017, personal communication) as from collection and sorting, as waste samples at collection points show high fractions of, for example, non-aluminium within the collected aluminium. Literature reviews indicated for many materials high losses during collection, sorting and recycling processes, with 10%–13% for non-ferrous household goods and 60%–70% for aluminium packaging (Brunner et al., 2015). The EC will therefore establish 'rules for the calculation, verification and reporting of the weight of materials or substances which are removed after a sorting operation and which are subsequently not recycled, based on average loss rates for sorted waste' (Official Journal L 150, 2018). Furthermore, it is unclear to what extent non-packaging aluminium waste is delivered to collection points, respectively, how much aluminium from packaging is collected and recycled through informal collection and does not find its way into official records. The absence of a well-organised collection scheme leads to illegal littering and increased sorting mistakes in bins or containers (Seyring et al., 2015).

In the future, the output of any sorting operation has to be reported 'as the weight of the municipal waste recycled [which] is sent into a final recycling process' (EC, 2015b). A report by Eunomia (2014) 'has indicated that currently the point at which Member States report the quantity of metals recycled varies across countries, and includes the following approaches:

- Material collected for recycling;
- Output from sorting plants;
- Materials sent from scrap dealers to reprocessors; and
- Materials received at smelting plants'.

Discussion and conclusions

The EU recycling targets, which are mandatory under the CEP for aluminium packaging (50%) by the end of 2025, have already been met by a majority of the Member States investigated. Only two out of 11 surveyed countries were lagging behind by more than 15% 10 years before the deadline. These figures indicate that at least the countries with a more advanced waste management have already achieved, or will succeed in fulfilling the CEP specifications regarding recycling rates for aluminium-packaging. If so, the question arises why the originally intended recycling rates in the CEP of 75% for 2025 have been reduced by one-third? It is known that the splitting of metal recycling rates into ferrous metals and aluminium in particular has been a major criticism during the negotiations on future recycling rates. But there are no publicly available documents for the course of the negotiations between the EU Member States, and the decision-making processes are not very transparent (Bundesministerium für Nachhaltigkeit und Tourismus, 2018, personal communication). The reasons for the decision in favour of lower recycling rates can only be speculated upon. In any case, for example, a postponed adaptation for countries with low rates, as was also the case in the Directive 94/62/EC on packaging and packaging waste, would have been possible.

The purpose of this study was to identify possible relationships between different waste management systems and quantities recycled from the various systems (separate collection, deposit refund system, informal collection, BA treatment or MT of MSW) in order to eventually draw conclusions about best practices. Based on the reported data, it was not possible to draw any conclusions about a relationship between recycling rates and collection, respective of waste treatment systems in place. It only seems permissible to assert that a DRS together with selective collection leads to a higher overall collection rate. This does not necessarily lead to a higher recycling rate, but reduces the likelihood of losses that can arise with further waste processing. During the combustion process, losses of metallic aluminium occur through oxidation and other chemical reactions, depending on material thickness, combustion temperature, residence time and contamination from salt (Hu et al., 2011).

It must be reiterated that it was not the task of this study to question or verify the data received from national authorities. Rather, the intent was to compare the data and point out obvious or hidden inequalities in the creation or presentation of the data.

However, a comparison was difficult owing to multiple differences across EU Member States, both in terms of input (import and exports) and output quantities (non-packaging waste, impurities). Indeed, the fact that all data must relate solely to the generated and recycled weight of aluminium packaging waste within the Member States and that unrelated quantities are to be disregarded seemed to have been neglected. Moreover, the inconsistencies and shortcomings of a lot of data enhances the inaccuracies and, of course, is reflected in waste and recycling quantities.

Based on the results, the following recommendations for action are put forward to improve the implementation of the current EU recycling strategy. The authors propose a clearer assignment of the corresponding data and more extensive mandatory reporting on losses and shares of packaging and non-packaging, imported and exported waste. These data are generally retrievable, but there must be a political will to create measures to link the available data. Periodic analysis of non-material related substances in separate collection and recovery from BA and MT have to be conducted in order to report net quantities of recovered aluminium. Product-specific MMSW analysis should be carried out at regular intervals in order to verify input quantities (differentiated between packaging and non-packaging) and to be able to estimate the recovery potential. Introducing a mandatory reporting system would require a high level of organisational effort and associated costs. The latter, in particular, is likely to provoke opposition mainly from business associations pointing to the unprofitable nature of the measure.

Further information on data sources and calculations are provided in supporting information on the Journal's website.

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Supplemental material

Supplemental material for this article is available online.

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How to increase recycling rates. The case of aluminium packaging in Austria

Rainer Warrings and Johann Fellner

Abstract

The recycling of aluminium (Al) packaging as a single fraction is a new obligation within the Circular Economy Package of the EU, with mandatory recycling rates of 50% for 2025 and 60% for 2030. The case study of Al packaging in Austria has been chosen to assess if and what measures need to be taken to achieve these recycling rates and what costs arise from these measures. In particular, the following options of Al recovery, and combinations thereof, have been investigated: bottom ash (BA) treatment; material recovery facilities (MRF) for mixed municipal solid waste; and changes to the selective collection system. The results of the study reveal that the present recycling rate of 55% for A1 packaging in Austria might be improved most significantly by MRF (up to 94%) and advanced BA treatment (up to 72%). Only minor improvements in the recycling rate (+2%) are achievable via a change in the collection system from selective metal to a mixed selective collection (joint collection of metal and lightweight packaging). If the only aim were to increase the recycling rates for Al packaging beyond the future target of 60%, an improvement in the Al recovery rates from BA treatment would be sufficient. With regard to increased recycling quantities of all recyclables, plastics in particular, the implementation of complex systems such as MRF makes sense, even if this results in higher costs for Al recovery (increasing from the current 480 to 640 € t^{-1} of recycled Al).

Keywords

Aluminium packaging, recycling, circular economy, collection, material recovery facilities, bottom ash treatment

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Introduction

The European Commission has presented an ambitious Circular Economy Package (CEP) with the intention of reducing resource depletion and waste generation and protecting the climate and the environment. The CEP is also based on the firm conviction that a circular economy is the only way in which the economy can grow and, ultimately, create sustainable jobs in the EU while making it possible to mitigate vulnerabilities because of strong resource dependency (European Commission, 2014). An essential cornerstone of this policy is the enhanced recycling and reuse of materials such as metals, plastics or glass from commodities and goods. This is especially important for packaging because this is mostly designed for single use and is rarely reused. The recycling rates incorporated into Directive 2018/852, which amends Directive 94/62/EC on packaging and packaging waste, demand the recycling of 50% of plastics, 25% of wood, 70% of ferrous metals (Fe), 50% of aluminium (Al), 70% of glass and 75% of paper and cardboard by 2025. Even higher levels are required by 2030 (European Union, 2018). The reporting of recycling rates for Al packaging as a single fraction is a new obligation. To date, only an overall rate (50%) for the recycling of metal packaging has been required (European Commission, 2004). The point of calculation for the recycling rate is the introduction of sorted metals into a metal smelter or a melting furnace. The Al concentrate derived from bottom ash (BA) must not contain materials other than Al. Furthermore, all Al included in the recycling rate must come exclusively from packaging waste (European Commission, 2019).

The future recycling targets for Al packaging could be challenging for some EU member states (Pivnenko et al., 2015; Reck and Graedel, 2012). Moreover, it is unclear what measures are to be taken to reach the targets and also which of these are the most efficient in terms of costs and environmental impact (Söderholm and Ekvall, 2020).

Hence, the aim of the present article is to evaluate what measures need to be taken to secure future mandatory recycling rates for Al packaging and what costs arise from these measures. In particular, the following research questions are addressed:

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- What measures of Al recovery (e.g. improved selective collection, recovery from waste incineration BA or material recovery facilities (MRF)) for mixed municipal solid waste (MMSW) are the most promising for reaching future targets?
- What economic costs arise from these measures?
- Could a correlation between Al recycling rates and specific costs per tonne of recycled Al packaging provide meaningful conclusions about the achievement of future recycling targets and help in making a decision about the most cost-efficient choice?

In recent years the authors have conducted detailed analyses of Al flows (Buchner et al., 2014; Warrings and Fellner, 2018) in Austria; because of this, the management of Al packaging in Austria has been chosen as the case study to assess if and what measures need to be taken to secure future recycling targets and what costs arise from these measures.

Materials and methods

As a first step towards answering the research questions given above, the status quo of Al packaging management in Austria has been analysed. Second, different scenarios for the improved recovery of Al packaging waste have been developed and assessed in relation to recycling rates achievable and the associated costs, expressed in euros per one tonne of recycled Al. To assess the recycling rates of the different scenarios, a material flow analysis (MFA) for Al packaging was conducted. In so doing, transfer coefficients for the recovery of Al packaging were applied to the different processes considered in the respective waste management scenarios.

MFA and scenarios

At present, the recycling of Al packaging in Austria takes place through selective collection (bring and door-to-door systems) and the treatment of municipal solid waste incineration (MSWI) BA. This system is assumed to be the reference system (S0), which will be compared with the alternative scenarios.

In the present study, six alternative scenarios (S1–S6) for the management of Al packaging waste (see Table 1) have been investigated, and different specifications have been considered for three of these (S2, S4, S6). The scenarios considered include measures at different stages of waste management:

- selective collection of Al packaging;
- upstream MRF for MMSW; and
- Al recovery from MSWI BA.

Basically, three main scenarios (S1, S2, S3) were chosen, reflecting the fact that the recycling of metals from MMSW in Austria is based on three processes, namely, selective collection, recovery from MSWI BA and mechanical treatment of MMSW. Therefore, improvements to the existing technologies in relation to these three processes were evaluated first. With regard to the separation of Al packaging from MMSW, the option of implementing sophisticated MRF (e.g. using sensor-based sorting methods) was considered. This was partly because the Austrian waste management industry is already planning to introduce such plants in the near future. These can separate plastics, paper and glass for recycling as well as metals.

In addition to the three main scenarios (S1–S3), the possibility of combining 'improved' processes was considered, for example, combining MRF installation and mixed selective collection (S4) or MRF and advanced BA treatment (S5). It was also examined whether installing MRF would make a selective collection obsolete (S6). In addition, with regard to the installation of MRF, it was considered whether a subsequent BA treatment would be necessary (S2b, S4b, S6b). All scenarios are summarized in Table 1.

In accordance with the EU Waste Framework Directive, the term 'recovery', as used in the current article, refers to 'waste serving a useful purpose', which, generally, includes the reuse of waste and energy recovery from waste as well as materials recycling. In addition, the term 'recovery' is used here for the process of separation (recovery) of Al packaging from different wastes that is then made available for subsequent recycling.

In relation to the MFA conducted in accordance with Brunner and Rechberger (2017), the input and output flows of Al packaging (market volume, MMSW collection, selective collection, MRF, MSWI, BA treatment) were determined on the basis of information obtained from local and national authorities and plant operators and supplemented by information from the literature. From these data, the transfer coefficients for the quantity of recovered Al packaging compared with the quantity of Al packaging treated or placed on the market were determined. Improvements to the individual waste management processes for recovering Al packaging (selective collection, MRF, BA treatment) change these transfer coefficients. The sum of the recovery from the individual processes results is the total amount of recycled Al packaging. The general MFA system used for the analyses is shown in the supplementary material (see Figure A1).

In addition to the assessment of the Al recycling rates for the different scenarios, the respective costs (operating and investment) were calculated. For the cost analysis, the net costs of the processes involved were calculated on the basis of the treatment costs and the revenues from the sale of the recycled materials. Because Al was recovered in all processes together with other recyclable materials (such as copper or steel scrap), the proportion of Al in the total treatment costs and revenues was calculated. These specific net costs of Al recovered by the different processes allowed for a final assessment of the net costs of Al (in € t^{-1} Al) for the different scenarios.

Finally, because the cost calculation is based on a large number of parameters, a sensitivity analysis was carried out to verify the data and to evaluate the influence of individual parameters on the final results (see sensitivity analysis).

Description of data used

General information. In most European countries, as in Austria, manufacturers must pay a licence fee (extended producer responsibility (EPR)) for the marketed packaging. The market volume of Al packaging is, hence, determined by the amount of licensed

Table 1. Scenarios investigated for the management of Al packaging waste.

Scenarios		Al recovery processes						
S0	Status quo	Selective collection	+		+	MSWI	+	Standard BA treatment
S1	Mixed selective collection	Mixed selective collection	+		+	MSWI	+	Standard BA treatment
S2a	MRF	Selective collection	+	MRF	+	MSWI	+	Standard BA treatment
S2b	MRF w/o BA treatment	Selective collection	+	MRF				
S3	Advanced BA treatment	Selective collection	+		+	MSWI	+	Advanced BA treatment
S4a	Mixed selective collection + MRF	Mixed selective collection	+	MRF	+	MSWI	+	Standard BA treatment
S4b	Mixed selective collection + MRF w/o BA treatment	Mixed selective collection	+	MRF				
S5	Mixed selective collection + advanced BA treatment	Mixed selective collection	+		+	MSWI	+	Advanced BA treatment
S6a	MRF w/o selective collection		+	MRF	+	MSWI	+	Standard BA treatment
S6b	MRF w/o selective collection and w/o BA treatment		+	MRF				

MRF: material recovery facilities; BA: bottom ash; MSWI: municipal solid waste incineration; w/o: without.

Al packaging. Al packaging comes almost exclusively from household packaging; commercial Al packaging under EPR is virtually non-existent (ARA, 2019). It is generally assumed that the market volume of Al packaging equals its waste generation because of its short life span. A study on packaging by TB Hauer et al. (2015) confirmed that the amount of Al packaging that was collected selectively and present in MMSW was similar to the amount of licensed Al packaging. There is an informal scheme for collection of Al packaging (Al cans) in Austria, but the quantities involved, as well as those resulting from littering, are negligible (Huber-Humer et al., 2018; Seyring et al., 2015). The selective collected quantities are those reported by the compliance schemes (ARA, 2019) and correspond to the quantities calculated from the difference between the market quantities and the quantities found in the MMSW (TB Hauer et al., 2016).

In Austria, MMSW is thermally treated in eleven MSWI facilities and, subsequently, the residues are treated in BA processing plants. The technology currently used in Austria makes it possible to detect and recover lumps of Al larger than 3–4 mm, whereas smaller lumps remain in the residues. Only very efficient eddy current separators (ECS) are able to separate significant amounts of Al from the fine fraction (0–6 mm) of the BA (Fuchs and Schmidt, 2013), which contains 40%–60% of the total Al present in MSWI BA (Allegrini et al., 2014; Berkhout et al., 2011; Biganzoli, 2013). No data are available on the actual quantities of metals recovered from BA treatment for all treatment facilities in Austria. However, based on figures from the biggest BA treatment facility in Austria (which processes about 48% of the overall amount of MSWI BA) and the fact that most other BA treatment plants in Austria use a similar technology, the recovered quantity of Al could be assessed.

The recycling of Al packaging waste incurs costs that are offset by revenues from the sale of Al scrap. For the cost analysis, all costs associated with the management of Al packaging waste have been considered, including the costs for separate collection of Al packaging, for collecting Al packaging via MMSW and for the thermal treatment of MMSW prior to BA treatment. Moreover, the costs for the recovery processes, such as BA treatment or MRF, have been accounted for. The costs and revenues of the scenarios investigated were obtained from the operators at the corresponding facilities or taken from the literature (see Table A3 in the supplementary information).

All data refer to 2018 unless stated otherwise. For the analysis conducted, it is assumed that the transfer coefficient remains the same irrespective of changes to any relevant data (marketed, selective collection and recovery volumes).

Discrimination between Al packaging and non-packaging from MMSW. Al collected selectively or present in MMSW is derived from both packaging and non-packaging like coffee capsules, coins or items like fittings or tubes. In the present article, the recovery and recycling of Al from packaging only is investigated. Therefore, it is necessary to distinguish between Al from packaging and A1 from non-packaging. In the following, a described description is given of how the proportion of Al from packaging compared with the total amount of Al present in MSW has been assessed.

At selective collection, Al packaging and non-packaging are sorted into different waste streams by manual re-sorting. Hence, the quantities of packaging waste reported by the compliance schemes refer exclusively to Al from packaging.

With regard to the quantities of Al recovered by MRF it was assumed that the ratio between Al packaging and non-packaging equals the ratio of the input to these facilities and, thus, the ratio present in MMSW. For the latter, data from waste sorting analyses in different Austrian provinces were available (Amt der Vorarlberger Landesregierung, 2015; FHA et al., 2014; Land Salzburg, 2013; Salzmann Ingenieurbüro, 2000; TB Hauer et al., 2016).

Al packaging that is not collected selectively or processed in MRF is incinerated as part of MMSW in MSWI. Incineration causes loss of metallic Al as it is partly transformed into fine-grained fly ash (FA) and partly converted into Al oxide (Al_2O_3). Al from packaging is more likely to oxidize or be released more frequently to FA than Al from non-packaging because thinner Al sheets and foils are used for the production of Al packaging (Kammer, 2014). Because Al melts during the combustion process at 600°C and nuggets are formed (Bunge, 2015), often in conjunction with other materials, Al particles found in BA cannot be recognized by their origin (packaging or non-packaging). To determine the quantities of Al from packaging present in BA, the input of Al from packaging into MSWI and the respective losses of Al from packaging via oxidation and FA were calculated using oxidation rates from a study by Biganzoli et al. (2012) and the distribution of material thickness between packaging and non-packaging from a study by Warrings and Fellner (2018). In relation to the recovery of Al from BA, detailed information on recovered volumes of non-ferrous metals was provided by the largest BA plant operator in Austria. In addition, data on the Al content in BA from different Austrian waste incineration plants (see Huber et al., 2019) were utilized and combined with the losses to FA and Al oxide identified by Warrings and Fellner (2018) to determine a representative transfer coefficient for the recovery of Al packaging from BA.

Description of processes applied for improved recovery of Al packaging waste. In the following, the different processes for improved recovery of Al packaging and, in particular, the data used for the processes are described in detail. In general, the current system of selective collection and recovery from BA on which Al packaging recycling in Austria is based was maintained, but it was expanded by the measures described below.

As far as the existing system of selective collection is concerned, a study by ARA (2019) suggests that an increase in Al collected separately could be achieved by switching from a separate metal collection to a mixed collection of lightweight packaging (wood, ceramics, plastics, bonded materials, textile fibres) and metal packaging (Fe, Al), as well as by an expansion of kerbside (door-to-door) and bring collection systems. The primary goal of such a change in the collection system would be to increase the collection of plastic packaging. Therefore, the increase in Al collected is seen as a positive side effect.

As already mentioned above, another option for improving the recovery of Al packaging is the installation of MRF for MMSW, which is considered to be an upstream waste treatment before MSWI takes place. Because a significant amount of Al packaging is lost during waste incineration (e.g. oxidation, generation of small Al particles), it seems logical to separate Al before combustion. MRF are automated or semi-automated sorting facilities that separate mixed and co-mingled materials into separate material streams: saleable recyclables; and residual streams that contain no or very few recyclable and recoverable materials for final disposal (Cimpan et al., 2015; Pomberger and Küppers, 2017).These facilities are modular systems and can be used for different purposes, but are becoming more popular for waste management because of the high recovery of secondary raw materials such as plastics, metals, paper, wood and glass, including biowaste (Dougherty Group, 2006). In this article, the use of MRF for the recovery of Al packaging from MMSW is investigated. Following this, using different scenarios (S2, S4, S6), the implementation of MRF for the pre-treatment of all MMSW in Austria is considered.

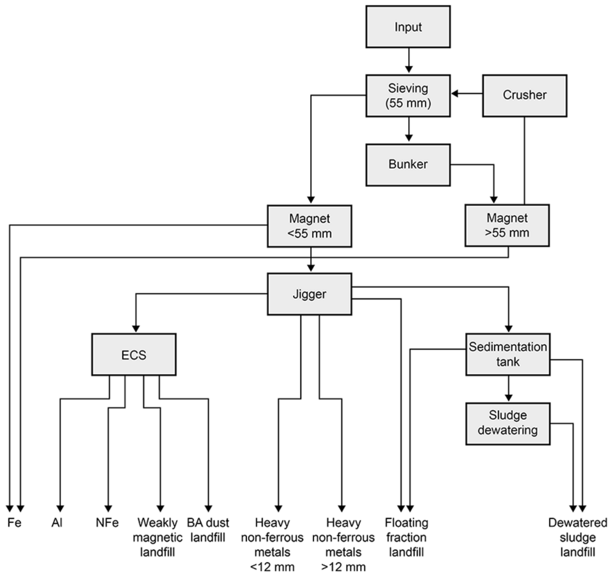

Figure 1. Processing scheme in an advanced BA treatment plant (modified version based on Stockinger (2016)).
Fe: ferrous metals; Al: aluminium; NFe: Non-ferrous metals; BA: bottom ash; ECS: eddy current separators.

Metals (Fe and non-ferrous) are typically separated from MSWI BA by means of magnetic separators and ECS. An advanced BA treatment process, which has been developed by an Austrian company (see Figure 1), has integrated several additional processing steps. As well as the commonly used sieve, crusher and ECS, it has a jigger and a sludge dewatering mechanism (Stockinger, 2016). In the present article, this type of BA treatment is considered to be an advanced BA treatment method and it is assumed that it is applied to all MSWI BA generated in Austria. The first step in the process is screening, which separates out all particles larger than 55 mm. These are fed back to the plant from time to time after passing through a crusher. The metallic particles larger than 55 mm are discharged by a specific sieve lining or are separated manually. A magnet separates out Fe smaller than 55 mm, whereas the mineral fractions and non-ferrous metals are fed into a jigger, in which a friction washer causes the particles to disintegrate for better subsequent metal recovery. The jigger produces four fractions (floating fraction, floating fraction heavy non-ferrous metals, lightweight fraction and sludge). The heavy non-ferrous metals are extracted and the lightweight fraction, which contains the Al, is fed to the ECS via an upstream magnetic drum, whereas the floating fractions and sludge are disposed of to landfill.

With regard to the two scenarios that examine advanced BA treatment (S3 and S5), the installation of three such treatment plants (each having a capacity of 100,000 t a^{-1}) was considered to be sufficient for processing the quantities of BA arising from MSWI in Austria.

Detailed information on the transfer coefficients of the different processes is provided in the supplementary information (Table A1).

Costs of various collection and waste management systems. The recycling of Al packaging involves costs that vary from one system to another, depending mainly on the type of plant, the technology used and the quantities processed. Essentially, the costs consist of capital costs, that is, costs in relation to the land required, the construction of the facility and the establishment of infrastructure, and also the acquisition costs of the machinery, vehicles and other items required, and operational costs, that is, personnel, energy, maintenance, service and other operating costs (Bohm et al., 2010). Typically, in all collection and waste management systems, other recyclables (Fe, non-ferrous metals, paper, plastics, etc.) as well as Al are treated and recovered. The specific costs for the recovery of the individual recyclables were calculated by multiplying the overall costs of the respective treatment process by the proportion of the revenues generated by the individual recyclables compared with the total revenues generated. This allowed the net costs (difference between costs of the recovery of the recyclables and the revenues generated) for the recovered Al packaging to be determined. As far as selective collection (ARA, 2019), MMSW collection (Stadt Wien MA 48, 2019) and MSWI (Brunner et al., 2015) were concerned, only net costs were available. For comparison, the costs and revenues for the different scenarios were calculated per one tonne of recycled Al packaging.

The net costs of Al (in € t^{-1} recycled Al) for the specific scenarios were calculated by multiplying the net costs of the individual processes by the amounts of Al treated in the respective processes, which were then divided by the total amount of recycled Al. The necessary information pertaining to the costs and revenues of the different processes considered was provided by the plant operators or taken from literature (ARA, 2019; Brantner, 2019; Bunge, 2015; Cimpan et al., 2015; Environment Media Group, 2020; Pressley et al., 2015; Stadt Wien MA 48, 2019; Stockinger, 2016).

Information on the specific costs of the different processes investigated is summarized in the supplementary information (see Table A2).

Sensitivity analysis. The calculation of net costs and recycling rates is based on input values that represent the most likely or expected values. Changing these parameters can lead to different results. A sensitivity analysis was carried out to assess the influence of input values on the results. A Monte Carlo simulation with 10,000 iterations was performed for each scenario using MS Excel® and @Risk 7.6 (Palisade, 2018). Using regression analysis, it was possible to identify which input parameter has a significant influence on the results when altered. The closer the correlation coefficient is to +1 or -1, the stronger the two variables are related positively or negatively. The coefficient of determination R^2 is a statistical measure of how well the regression predictions approximate the real data points. The closer the certainty measure is to 1, the higher the quality of the regression predictions. In addition to determining regression coefficients, an examination as to how the net costs of the different scenarios change when varying the input parameters by +/- 30% of the initial value was carried out. Detailed information on regression coefficients and the variability of input values and results is provided in the supplementary information (Tables A1–A13 and Figure A3).

Results

Aluminium recycling rates for the scenarios investigated

The total mass of Al packaging waste in Austria in 2018 amounted to 20,100 t a^{-1} (tonnes per year), of which 36% was collected selectively and 19% was recovered from MSWI BA processing. The recycled amount of Al packaging was, therefore, around 11,200 t or 55% (S0). Six scenarios (S1–S6) were investigated to see if they would increase the recycling rates of Al packaging compared with the status quo.

Before the results of the scenarios investigated are presented and discussed, the impact of implementing improvements to single processes (mixed selective collection, advanced BA treatment and MRF) for the recovery of Al from packaging waste is shown. For example, a change to mixed selective collection would increase the proportion of Al packaging recovered via selective collection from 36% to 39% (7200 to 7800 t a^{-1}). The use of an advanced BA treatment instead of a conventional BA treatment would raise the recovery rate of Al packaging from BA from 37% to 66% (4000 to 7100 t a^{-1}), which equals 19%–20% of the total Al packaging waste generated. According to Pressley et al. (2015), MRF is capable of separating 87% of Al packaging from MMSW. This corresponds to 30%–31% of the total Al packaging waste. All transfer coefficients applied to the recovery of Al packaging can be found in the supplementary information (Table A1 and Figure A2).

The results of the scenarios examined (S1–S6) show a significant increase in recycled Al packaging (see Table 2) compared with the status quo (S0). If MRF (S2, S4, S6) are implemented nationwide, up to 94% (19,100 t a^{-1}) of the total of Al packaging could be recycled, which represents the highest rate of all the scenarios investigated. The total abandonment of selective collection when MRF is installed (S6) would reduce the recycling rate of Al packaging to 91% or 18,300 t a^{-1} (S6a) and to 87% or 7500 t a^{-1} (S6b) if no BA treatment is used. The type of selective collection in combination with MRF (S2a and S4a) has only a negligible impact on the recycling rate. The implementation of advanced BA treatment leads to 71% or 14,300 t a^{-1} (S3) and 72% or 14,500 t a^{-1} (S5) of Al packaging being recycled. If the only measure is to switch to mixed selective collection (S1), this will result in a slight increase of 2% in the recycling rate to 57% or 11,600 t a^{-1}.

For some of the scenarios, the overall transfer coefficients for Al packaging are shown in Figure 2. Figure A2 in the supplementary information provides an insight into the transfer coefficients for Al packaging for all scenarios.

Costs of aluminium recovery for the scenarios investigated

The net costs of recycling one tonne of Al packaging during the reference period (May 2020) are €480 (S0). These include all costs and revenues of all the processes that contribute to or are necessary for the recovery of Al packaging (see Table 3).

Table 2. Recycling rate and recycled quantity of Al packaging for the different scenarios.

Scenarios		Al packaging recycled	Recycling rate
		t a^{-1}	%
S0	Status quo	11,200	55%
S1	Mixed selective collection	11,600	57%
S2a	MRF	19,000	94%
S2b	MRF w/o BA treatment	18,500	92%
S3	Advanced BA treatment	14,300	71%
S4a	Mixed selective collection + MRF	19,100	94%
S4b	Mixed selective collection + MRF w/o BA treatment	18,600	92%
S5	Mixed selective collection + advanced BA treatment	14,500	72%
S6a	MRF w/o selective collection	18,300	91%
S6b	MRF w/o selective collection and w/o BA treatment	17,500	87%

MRF: material recovery facilities; BA: bottom ash

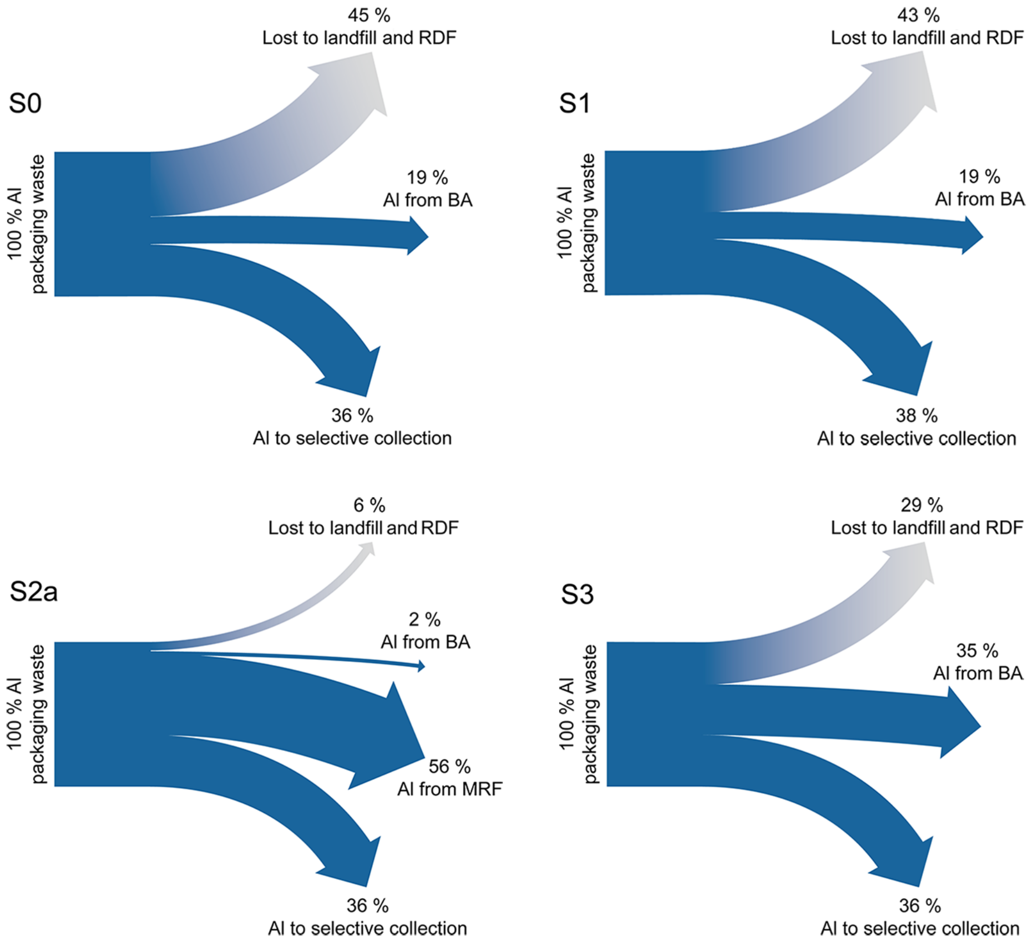

Figure 2. Transfer coefficients of Al packaging for selected scenarios.
Al: aluminium; RDF: refuse derived fuel; BA: bottom ash; MRF: material recovery facilities.

Hence, all calculations include the costs for the collection of MMSW (114 € t^{-1} Al) and the costs for MSWI (100 € t^{-1} Al) when Al is recovered via BA treatment. The costs for MSWI were then added to the costs of Al recovery via BA treatment. This also explains why the net costs for conventional BA treatment (670–690 € t^{-1} Al) are the highest of all process net costs. In the case of advanced BA treatment, the net costs drop to 130–150 € t^{-1} Al simply because of the fact that higher total recovery rates of metals also reduce the net costs for Al recovery. In contrast, MRF treatment prior to waste incineration and subsequent BA treatment increases the net costs for BA treatment to 2700–2840 € t^{-1} Al because of the low content of metals present in BA and, thus, the low revenues achievable by their recovery. The process net costs for selective collection are reduced from the current

Table 3. Costs and revenues of Al recycling for the different processes (given in € t^{-1} recovered Al).

		Scenarios	Status quo	Mixed selective collection	MRF	MRF w/o BA treatment	Advanced BA treatment	Mixed selective collection + MRF	Mixed Selective Collection + MRF w/o BA treatment	Mixed Selective Collection + advanced BA treatment	MRF w/o selective collection	MRF w/o Selective Collection + BA treatment
		Unit	S0	S1	S2a	S2b	S3	S4a	S4b	S5	S6a	S6b
MRF	Net costs: Al from MRF	€ t^{-1} Al			590	590		590	590		590	590
BA treatment	Net costs: Al from BA treatment	€ t^{-1} Al	670	690	2700		130	2840		150	1640	
Collection	Net costs: Al from selective collection	€ t^{-1} Al	380	340	380	380	380	340	340	340		
Total	**Scenario net costs**	**€ t^{-1} Al**	**480**	**450**	**570**	**510**	**260**	**540**	**480**	**250**	**640**	**590**
	Al recycling rate	**%**	**55%**	**57%**	**94%**	**92%**	**71%**	**94%**	**92%**	**72%**	**91%**	**87%**

MRF: materials recycling facility; BA: bottom ash; w/o: without.
Treatment costs (in € t^{-1} Al): MMSW 114; MRF 50; MSWI 100; BA treatment 28–30.
Proportion Al/total revenues: MRF 15%; BA treatment 26%.
Al transfer coefficient: MRF 0.87; BA treatment 0.37–0.66; Selective collection 0.36–0.39.
Sale price of Al scrap recovered (in € t^{-1}): MRF 500; BA treatment 600.

380–340 € t^{-1} Al if the switch to a mixed selective collection is made. This switch to mixed selective collection is necessary in any case to increase the recycling rates for plastic packaging. The 'average' net costs for recovering Al packaging from MMSW through MRF are 590 € t^{-1} Al.

As mentioned above, the net costs for Al (in € t^{-1} Al) for the specific scenarios were calculated by comparing the net costs of the individual processes and the quantities of recycled Al (in tonnes Al) with the total quantity of Al recycled through the individual processes. The results of the analysis indicate that out of all the scenarios investigated, the lowest net costs for Al recycling can be achieved by implementing scenario S5, in which Al recovery is based on mixed selective collection and advanced BA treatment. The net costs would be reduced from the current 480 to 250 € t^{-1} recycled Al. A change to mixed selective collection without any other measures (S1) would only slightly reduce the net costs to 450 € t^{-1} recycled Al.

Scenarios (S2, S4, S6) considering the installation of MRF would result in the highest net costs, ranging between 480 and 640 € t^{-1} recycled Al. Not carrying out Al recovery via BA treatment in scenarios S2b, S4b and S6b would reduce the net costs by 10%–15%. The use of MRF without selective collection of Al packaging (S6) has the highest net costs of all scenarios investigated at 590–640 € t^{-1} recycled Al. To make Al recovery from MRF competitive with recovery from advanced BA treatment, the treatment costs for MMSW in MRF would need to drop from 50 € t^{-1} to about 30 € t^{-1} processed waste. All calculations for MRF are based, among other things, on a very high transfer coefficient (87%) for Al recovery that was reported by the companies building MRF plants. If the transfer coefficient for Al recovery of MRF only corresponded to the transfer coefficient of 66% for advanced BA treatment, the net costs for Al recovery from MRF would increase by 160–250 € t^{-1} to 680–940 € t^{-1} recycled Al. This would also reduce the recycling rates for Al packaging from 91%–94% to 78%–79%, and to 66% without selective collection.

Sensitivity analysis for Al recycling rates and recovery costs

Input values used for the analyses (transfer coefficient, process costs, proportion of Al revenue compared with total revenues, sales price) have a significant influence on the results (recycling rates and net costs of scenarios). To assess this relationship, a multiple linear regression analysis was carried out as part of a sensitivity analysis (see supplementary information, Figure A3).

In all scenarios without MRF (S0, S1, S3, S5), which are based on selective collection and BA treatment only, the transfer coefficient for the recovery of Al via BA treatment has the highest influence on the net costs. There is a negative correlation between recovery rate and net costs, indicating that a decrease in the recovery rates of Al leads to an increase in net costs and vice versa. The regression coefficients for costs and sales price for Al via BA treatment and the proportion of revenue from Al in comparison with total revenues are moderate. There is only a very weak relationship

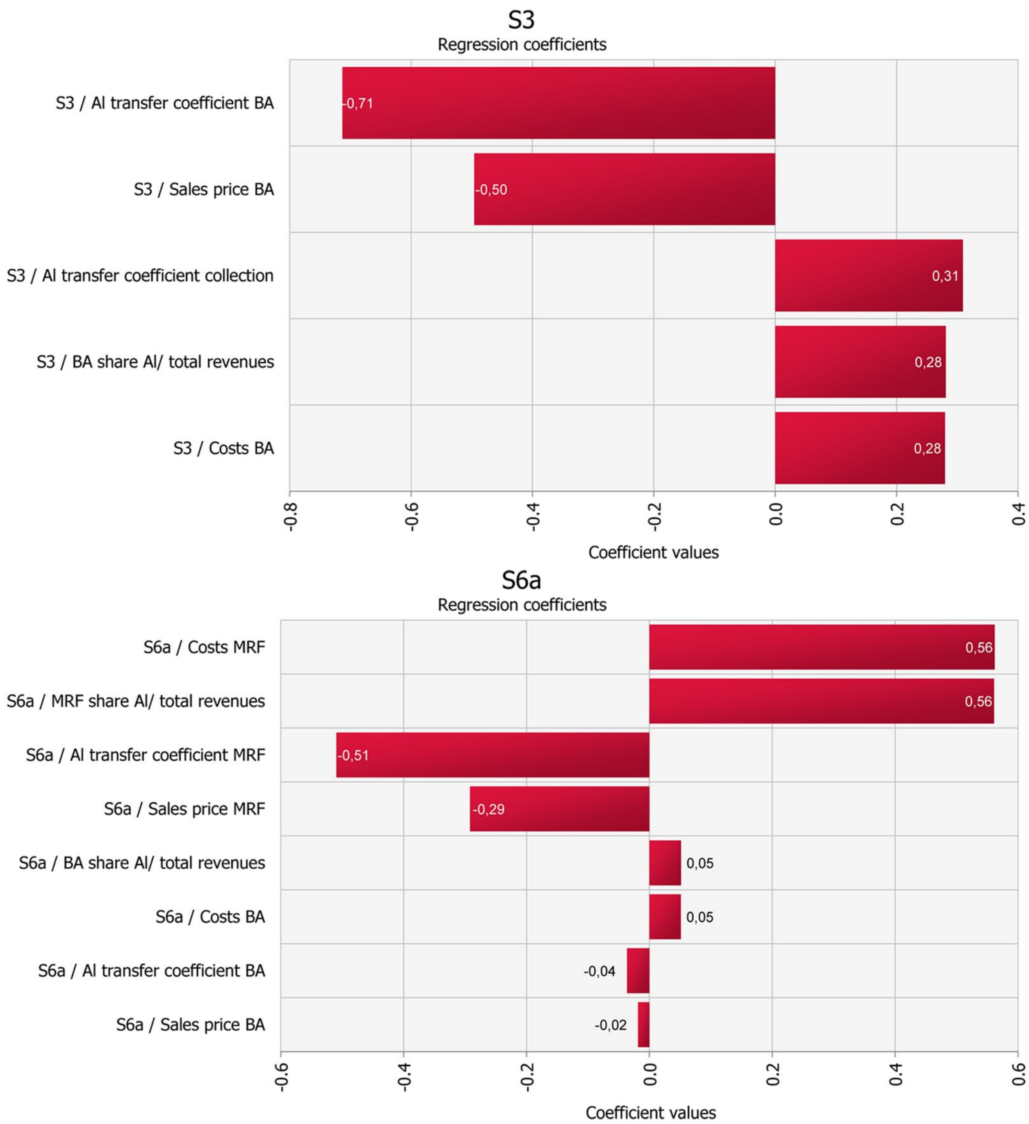

Figure 3. Regression coefficients for different input parameters with respect to the net costs of Al recovery for selected scenarios (S3 and S6a).
Al: aluminium; BA: bottom ash; MRF: material recovery facilities.

between the Al transfer coefficient for selective collection and the net costs when conventional BA treatment is used, but it becomes more important with advanced BA treatment.

In scenarios with MRF (S2, S4, S6), the input parameters in relation to the MRF process (transfer coefficient, costs, sales price and proportion of Al revenues) all have a similar moderate influence on the net costs of the scenarios, whereas the influence of the transfer coefficient on selective collection is weak. In Figure 3, the regression coefficients for selected scenarios are shown. A complete display of the regression coefficients for all scenarios is given in the supplementary information (Figure A3). The R^2 is for all parameters between 0.99 and 0.93, indicating a good model fit and that variations in the results can be explained adequately by variations in the input values.

Simulating concurrent changes in various input parameters by up to +/-30% confirms the results of the regression analysis (see supplementary information, Tables A4–A13). For scenarios without MRF (S1, S3, S5), a decrease in the Al recovery rate via BA treatment by 30% (relative change) would raise the net costs to 58% (S3, from 256 to 405 € t^{-1} recycled Al), whereas other parameters have only a moderate effect on the outcome. In scenarios with MRF, such as S6a, a change of 30% in the costs or transfer coefficient for Al recovery from MRF would raise the net costs from 635 to more than 900 € t^{-1} recycled Al.

Conclusions

The results of the analyses presented indicate that the required recycling targets for Al packaging according to the CEP for 2025 (50%) had already been reached in Austria in 2018 with 55%. However, the performance must be improved to achieve the target of 60% by 2030.

The quantity of 11,200 t Al a^{-1} that is currently recycled is achieved through selective collection (7200 t Al a^{-1}) and the recovery of Al via BA treatment (4000 t Al a^{-1}). Improvements made to selective collection through adjustments and changes (mixed selective collection) do not seem to be sufficient to meet the higher target (expected recycling rate of 57%).

The use of an advanced BA treatment is a cost-effective solution for achieving higher recycling rates for Al packaging (>70%). BA processing plants are comparatively simple to construct and operate and, therefore, not very expensive to implement.

The installation of MRF prior to MSWI is the most effective way of achieving very high recycling rates for Al packaging (over 90%), but it is associated with high costs because the construction and operation of such systems is quite complex and involves the use of a wide range of technologies. Because of the large number of recyclables and the associated revenues, the increase in net costs per one tonne of Al is moderate; however, in comparison with the other processes the net costs are highest (up to 640 € t^{-1} recycled Al). Manufacturers of MRF report very high recovery rates (87%), although studies on various existing plants show very different recovery rates. According to Cimpan et al. (2015), the potential efficiency of these plants with regard to Al recovery is 29%–95%. The installation of MRF, provided the high efficiency reported by the manufacturers is guaranteed, would allow high recycling rates to be achieved, not only for Al packaging but also for other waste materials such as plastic packaging. However, based on the results of the present study, the installation of MRF is not a substitute for selective collection of Al packaging because this would result in higher costs and lower recycling rates for Al packaging waste.

If the only aim were to reach the 2030 recycling target for Al packaging in Austria (60%), an improvement in Al recovery from BA treatment would be sufficient (Al recycling rates of 71%–72%), and would entail comparatively little effort and few costs. With regard to recycling quantities of all recyclables, plastics in particular, the implementation of complex systems such as MRF makes sense, even if this results in higher costs for Al recovery (increasing from today's 480 to 640 € t^{-1} of recycled Al). Such waste management scenarios including MRF would also achieve the highest recycling rates for Al packaging (91%–94%). If, however, the transfer coefficients for Al recovery from MRF do not correspond to the manufacturers' specifications and are approximately at the level of advanced BA treatment, the recycling rates for Al packaging reach a maximum of 79% when implementing MRF.

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Supplementary material

Supplementary material for this article is available online.

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