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Circular Economy of Packaging Aluminium – An analysis of the current practice and future potential
submitted in satisfaction of the requirements for the degree of Doctor of Science in Civil Engineering of the Technische Universität Wien, Faculty of Civil Engineering

Dissertation
Kreislaufwirtschaft von Aluminiumverpackungen - Eine Analyse von Status quo und zukünftigen Verbesserungspotentialen ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der technischen Wissenschaft eingereicht an der Technischen Universität Wien, Fakultät für Bauingenieurwesen von

DI DI Rainer Warrings
Matrikelnummer 01140210
Lenaugasse 19/1/11
1080 Wien

Supervisor: Assoc.Prof.Dipl.-Ing.Dr.techn. Johann Fellner
Technische Universität Wien
Institute for Water Quality and Resource Management
1040 Vienna, Austria

Auditor: Assoc.Prof.Dipl.-Ing.Dr.techn. Mario Grosso
Politecnico di Milano
DICA – Department of Civil and Environmental Engineering
20133 Milano, Italy

Auditor: Dipl.-Ing.Dr.techn. Andreas Bartl
Technische Universität Wien
Institute for Chemical Engineering
1040 Vienna, Austria

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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%\textsuperscript{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

\textsuperscript{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


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

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
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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 (Al₂O₃) 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 Al₂O₃. 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...
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 and 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$_2$O$_3$) through the reaction with oxygen. The conversion from Al oxide (Al$_2$O$_3$) 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.
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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.

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

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

Figure 1. Model overview for Al packaging & household non-packaging management
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 AI flows and model results.

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

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

<table>
<thead>
<tr>
<th>Data quality indicator</th>
<th>Sensitivity level</th>
<th>Score: 1</th>
<th>Score: 2</th>
<th>Score: 3</th>
<th>Score: 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coefficient of variation (CV, in %)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td>2.3</td>
<td>6.8</td>
<td>20.6</td>
<td>62.3</td>
</tr>
<tr>
<td>Completeness</td>
<td>High</td>
<td>0.0</td>
<td>4.5</td>
<td>13.7</td>
<td>41.3</td>
</tr>
<tr>
<td>temporal</td>
<td>Medium</td>
<td>0.0</td>
<td>2.3</td>
<td>6.8</td>
<td>20.6</td>
</tr>
<tr>
<td>geographic</td>
<td>Low</td>
<td>0.0</td>
<td>1.1</td>
<td>3.4</td>
<td>10.3</td>
</tr>
<tr>
<td>other correlation</td>
<td></td>
<td>4.5</td>
<td>13.7</td>
<td>41.3</td>
<td>124.6</td>
</tr>
<tr>
<td>Expert estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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).

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

<table>
<thead>
<tr>
<th>Country</th>
<th>Recycling of Al packaging through</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRS</td>
<td>Selective collection</td>
<td>BA/MT treatment</td>
</tr>
<tr>
<td>AT</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>BE</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>CZ</td>
<td>no</td>
<td>yes</td>
<td>-</td>
</tr>
<tr>
<td>DE</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>FR</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>GR</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>IT</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>NL</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>PT</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>SE</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>UK</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

**Figure 2. Evaluated waste management scenarios for Al packaging**
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

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Al recovery processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0 Status Quo</td>
<td>MMSW collection + Selective collection + MSWI + Standard BA treatment</td>
</tr>
<tr>
<td>S1 Mixed Selective Collection</td>
<td>MMSW collection + Mixed Selective Collection + MSWI + Standard BA treatment</td>
</tr>
<tr>
<td>S2a MRF</td>
<td>MMSW collection + Selective collection + MRF + MSWI + Standard BA treatment</td>
</tr>
<tr>
<td>S2b MRF w/o BA Treatment</td>
<td>MMSW collection + Selective collection + MRF</td>
</tr>
<tr>
<td>S3 Advanced BA Treatment</td>
<td>MMSW collection + Selective collection + MSWI + Advanced BA Treatment</td>
</tr>
<tr>
<td>S4a Mixed Selective Collection + MRF</td>
<td>MMSW collection + Mixed Selective Collection + MRF + MSWI + Standard BA treatment</td>
</tr>
<tr>
<td>S4b Mixed Selective Collection + MRF w/o BA Treatment</td>
<td>MMSW collection + Mixed Selective Collection + MRF</td>
</tr>
<tr>
<td>S5 Mixed Selective Collection + Advanced BA Treatment</td>
<td>MMSW collection + Mixed Selective Collection + MSWI + Advanced BA Treatment</td>
</tr>
<tr>
<td>S6a MRF w/o Selective Collection</td>
<td>MMSW collection - + MRF + MSWI + Standard BA treatment</td>
</tr>
<tr>
<td>S6b MRF w/o Selective Collection &amp; w/o BA Treatment</td>
<td>MMSW collection - + MRF</td>
</tr>
</tbody>
</table>

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.

![Circular representation of Al packaging & household non-packaging, Austria 2013](image)

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 $\text{Al}_2\text{O}_3$ 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)](image)

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.

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.

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”.

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The approved original version of this doctoral thesis is available in print at TU Wien Bibliothek.
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

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

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.
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.

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>MRF w/o BA Treatment</th>
<th>Advanced BA Treatment</th>
<th>Mixed Selective Collection + MRF</th>
<th>MRF + BA Treatment</th>
<th>MRF + BA Treatment + Mixed Selective Collection</th>
<th>MRF + BA Treatment + Advanced BA Treatment</th>
<th>MRF w/o Selective Collection + BA Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
</tr>
<tr>
<td>2</td>
<td>13,000</td>
<td>13,000</td>
<td>13,000</td>
<td>13,000</td>
<td>13,000</td>
<td>13,000</td>
<td>13,000</td>
</tr>
<tr>
<td>3</td>
<td>12,400</td>
<td>12,400</td>
<td>12,400</td>
<td>12,400</td>
<td>12,400</td>
<td>12,400</td>
<td>12,400</td>
</tr>
<tr>
<td>4</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
</tr>
<tr>
<td>5</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
</tr>
<tr>
<td>6</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
<td>20,100</td>
</tr>
</tbody>
</table>

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)

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

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)

<table>
<thead>
<tr>
<th>Recycling Process/Scenario</th>
<th>&lt;60%</th>
<th>60-70%</th>
<th>70-80%</th>
<th>80-90%</th>
<th>&gt;90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status Quo (S0)</td>
<td>480 €/t</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed selective collection (S1)</td>
<td>480 €/t</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced BA treatment (S3, S5)</td>
<td></td>
<td>250 to 260 €/t</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRF (S2, S4, S6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>480 to 640 €/t</td>
</tr>
</tbody>
</table>

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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