CO_2 emissions in the recovery and recycling of aluminium from MSWI bottom ash

Master Thesis

Universiteit Utrecht

Author: H.J.P. (Paul) Claassens
Student number: 3980103
Contact details: h.j.p.claassens@students.uu.nl
Master programme: Energy Science
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Supervisor: prof. dr. E. Worrell
2nd reader: dr. W.G.J.H.M. van Sark

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Abstract

In the Netherlands, aluminium and other metals are recovered from Municipal Solid Waste Incinerator bottom ash. Over the last years additional attention has been given to the recovery of non-ferrous metals especially, with the signing of a green deal between the Dutch Government and the Dutch Waste Management Association for instance.

For 2012, it is estimated that 41.2 ktonne metallic aluminium, in various alloy compositions, was incinerated as part of the waste. It is assessed that 14.2 ktonne clean aluminium was recovered and 19.2 ktonne metallic aluminium can additionally be recovered from the bottom ash. This can be done with recent developed and deployed technologies, such as Advanced Dry Recovery which is added to the existing systems, or other techniques in the future. Due to the incineration process 7.2 ktonne metallic aluminium is mainly lost to oxidation. The oxidation of aluminium to corundum (Al_2O_3) generates however an additional amount of energy on top of the combustion energy from the waste in the furnace. Based on the oxidation to corundum it is estimated that 0.19 PJ of energy is additionally generated on a total of almost 72 PJ.

In the supply chain that follows, 1.3 ktonne of additional losses will occur, after which 13.5 ktonne of aluminium ends up in semi-finished products, mainly as aluminium ingots. This gives an overall recycling factor of 33 %. The recovered aluminium will mainly be used to cast DIN 226 alloys, which are applied in for example engine parts.

In the recovery and recycling of aluminium from MSWI bottom ash 210.3 ktonne of CO_2 are emitted. Therewith it saves, compared with the production of primary aluminium produced in Europe, 7 940 kg CO_2 per tonne aluminium recycled and saves 34 % CO_2 emission, which would have be emitted with the production of the total amount of 41.2 ktonne primary aluminium produced in Europe. This in contrast, to the used comparison with regular aluminium scrap, where 97 % less CO_2 is emitted than primary aluminium.

The main challenge for the coming years is to reduce the amount of aluminium unrecovered in bottom ash, therewith increasing the emission savings.

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List of abbreviations

BATP	Bottom Ash Treatment Plant
DWMA	Dutch Waste Management Association
ECS	Eddy Current Separation
HMS	Heavy Media Separation
KGS	Kinetic Gravity Separation
LCA	Life Cycle Assessment
LIMS	Low Intensity Magnetic Separation
MDS	Magnetic Density Separation
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
NPRIW	Non-Process Related Industrial Waste
RDF	Rotary Drum Furnace

Chapter 1: Introduction

In the Netherlands, solid waste is incinerated in Municipal Solid Waste Incinerators (MSWIs). This waste contains aluminium from various sources, which can partly oxidise in the incinerator and thereby release energy. After the waste is incinerated, the remaining bottom ash still contains most of the metallic aluminium and other valuable metals. These valuable metals can be recovered from the bottom ash and are divided into two categories, namely ferrous and non-ferrous metals. The non-ferrous metals consist mainly of aluminium. Over the last years more attention has been given to the recovery of non-ferrous metals and it has been applied on a larger scale. The recovery of these metals could generate an additional income for the MSWIs, which is beneficial considering the current market conditions. Due to the introduction of new recovery techniques and improvement of the existing ones, the recovery of non-ferrous metals has increased over the last years. However, there is still a large potential to increase the amount of recovered metals.

The recovery of aluminium and other non-ferrous metals not only has a financial effect, it also has an environmental impact, since these metals could otherwise be considered a loss. Replacing the metal losses with primary aluminium has a significant impact, since the production of aluminium is very energy intensive and is therefore associated with large CO_2 emissions. The exact impact however depends on the region and their electricity mix.

Even though the recovery of metals from bottom ash is a niche market, research is performed into the environmental impact of this recovery (Biganzoli, et al., 2013) and the impact of several technologies is compared amongst each other (Muchova, 2010). An assessment of the CO_2 emissions of the entire production chain from the incineration of Municipal Solid Waste up to the recycling of aluminium into semi-finished products has to the authors knowledge, not yet been performed.

The CO_2 emission savings for secondary aluminium compared with primary aluminium are often used to indicate the environmental benefits for the recovery of aluminium out of bottom ash, but no publicly available research was found to confirm this claim.

In order to address these points, the following research question is formulated:

What is the CO_2 emission reduction related to the recovery and refinery of aluminium from MSWI bottom ash with the best available technology at this moment, compared with primary aluminium production and regular aluminium scrap recycling production in the Netherlands?

This research question is further divided into the following sub-questions:

1. How is aluminium recovered from MSWI bottom ash in the Netherlands with the best available technology?
2. To what extend is aluminium present in municipal solid waste, bottom ash and in the aluminium concentrate, and what is the oxidation grade throughout the process?
3. How is scrap aluminium and aluminium scrap, from Dutch MSWI in particular, recycled and what is the recovery and recycling rate in this system?
4. What are the energy requirements and CO_2 emission related to aluminium throughout the value chain of Municipal Solid Waste to recycled aluminium?
5. What are the energy requirements and CO_2 emission for primary aluminium and regular aluminium scrap recycling?

Chapter 2: Methodology

This chapter describes the methodology and scope used in order to determine the CO_2 emission related to the recovery and recycling of aluminium from MSWI bottom ash.

2.1. Methodology

For this research a Life Cycle Assessment (LCA) approach will be used to determine the energy demand for the recovery and recycling of aluminium from bottom ash. Based on the energy demand of these processes, the CO_2 emissions will be calculated.

The use of this approach means that there are differences compared to a full LCA study as is described in several ISO standards. While a full LCA study deals with four phases of a life cycle in which each cycle has its own needs for natural resources and produces its own products, waste and losses, this study only aims at three of them, namely the processing of the disposed products, the extraction, and the product manufacturing. The distribution and use phase is not considered due to the fact that it lays beyond the scope of this research.

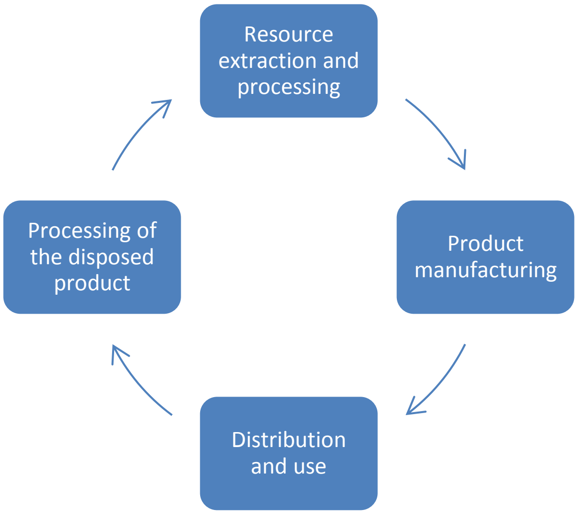

Figure 1: simplified life cycle [1]

Furthermore, this study only aims at the energy demand of this process and the therewith-associated CO_2 emission, in contrast to a full LCA study where 16 impact categories are addressed to give an overview of the total environmental impact. The CO_2 emissions will be determinate, based on a mass and energy balance over the system.

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[1] Source: Blok (2007)

2.2. Functional unit, scope and level of detail

Similar to a full LCA, the functional unit, goal, scope and level of detail are determined. Since the goal of this analysis is already set with the formulation of the research question, only the functional unit, scope and level of detail need to be established.

Functional unit

The functional unit in this research is the production of 1 tonne of aluminium ingot, recovered from MSWI bottom ash. This product can have different forms, as it is casted into different products, such as aluminium ingots or rolling slaps. The composition of the products may also differ depending on the desired alloy. For reasons of simplicity it is assumed that all products are cast into ingots.

Scope

The scope of this assessment is determined with the following parameters: time, region, energy requirements, CO_2 emissions and transport. This is summarised in the schematic overview in figure 2, which also serves to illustrate the system boundaries and as a chapter outline.

Time

The emission of CO_2 is determined for the year 2012 since this is the latest year on which most data is available. In case there is no data available for 2012, less recent data will be used.

Region

The analysis is limited to the Netherlands regarding the recovery of aluminium from bottom ash. However, the aluminium scrap market is an open market and the refinery and melting and casting is considered to take place throughout Europe. Therefore, the impact of these processes will be regarded as part of the system.

Energy requirements and CO_2 emissions

The CO_2 emissions are calculated for the direct energy use of the processes, including transport between and within the sub-systems. The emissions related to the electricity use, which has no direct emissions, are also incorporated.

The electricity within this system is either supplied by the national grid or generated by the MSWIs. This affects the emission factor since the primary task of MSWIs is the incineration of waste. The electricity produced replaces the production of electricity by other methods such as coal-fired power plants. Besides the replacement of regular produced electricity, electricity from MSWIs is also partly considered renewable energy. This will be considered in the assessment of the emissions.

Transport

The energy requirements and associated CO_2 emissions from transport between the different sub-systems and within the sub-systems are also assessed. Depending on the manner of transport an appropriate emission factor will be chosen expressed per tonne·km.

Level of detail

In this analysis a sector wide overview of the energy use and related CO_2 emission will be provided. However, the amount of energy could differ between the specific plants or processes within this scope.

These specifics are included if they affect the overall result, otherwise they are captured within the system borders and averaged values will be used.

Schematic overview and outline

In figure 2, a schematic overview of the investigated system is shown. This figure only represents the primary process regarding the aluminium recycling and recovery. In the different chapters the sub-systems will be closer examined. This includes for example the recovery of other products and the losses that occur. The emissions of CO_2 is not directly shown in figure 2, but is directly associated with the use of energy.

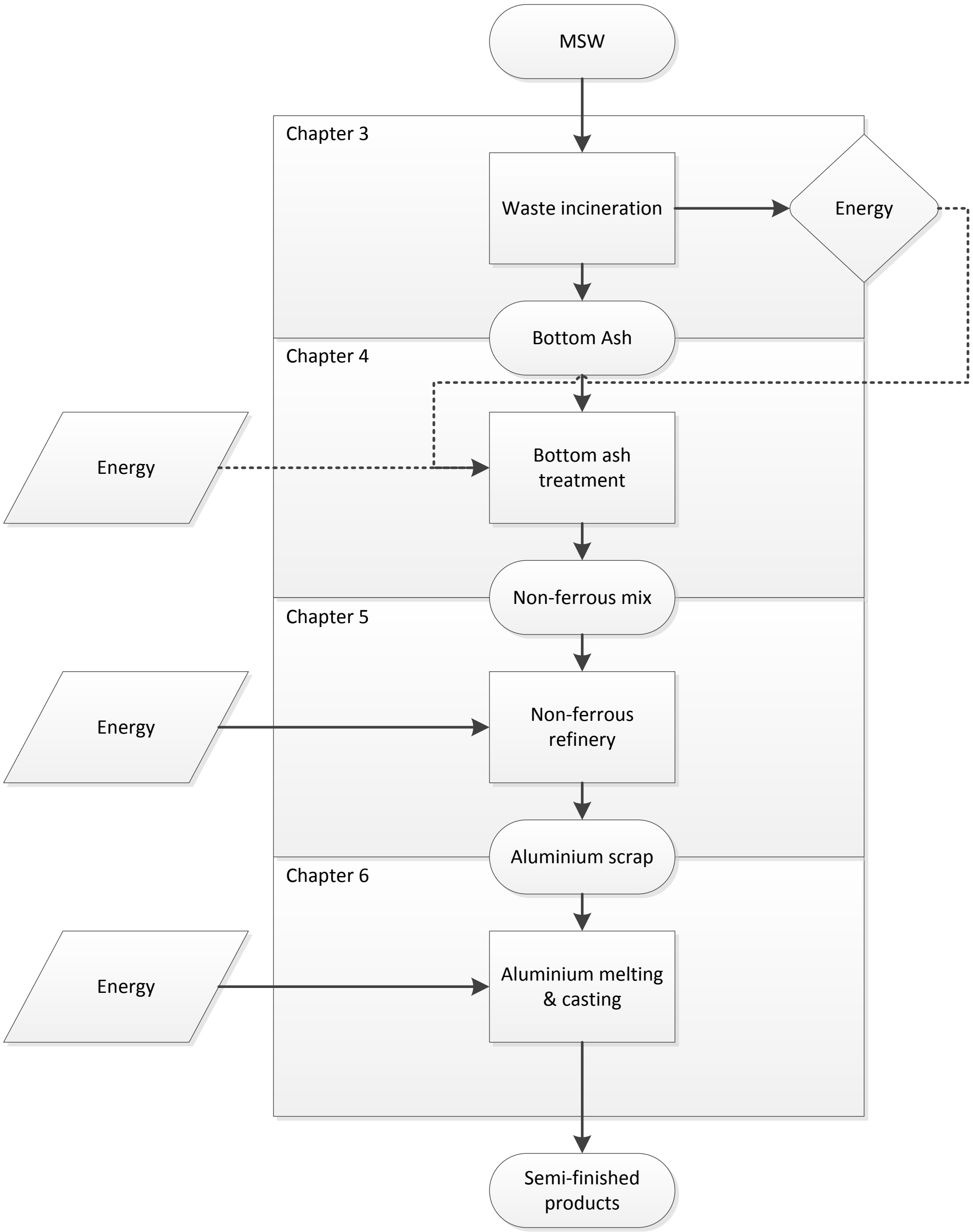

Figure 2: schematic overview of the scope

2.3. Uncertainty and sensitivity

The values presented in the following chapters can be considered as the most likely scenario, based on the available literature. However, these values will most likely have a certain degree of uncertainty. Therefore, an uncertainty and sensitivity analysis will be performed in the discussion section at the end of this thesis.

Chapter 3: Municipal Solid Waste Incineration and its effect on aluminium in it

3.1. Introduction

The incineration of Municipal Solid Waste (MSW) has an effect on the amount of metallic aluminium in the waste, since it oxides part of the metallic aluminium into aluminium oxide, which can be considered as a loss of metal. In order to get an overview and in depth understanding of the processes involved during the incineration of waste, they are analysed and described in this chapter. Furthermore, an analysis is performed to determine the amount of aluminium present in Municipal Solid Waste and the effect of different processes on this amount. An overview of the sub-system dealt with in this chapter is shown in figure 3.

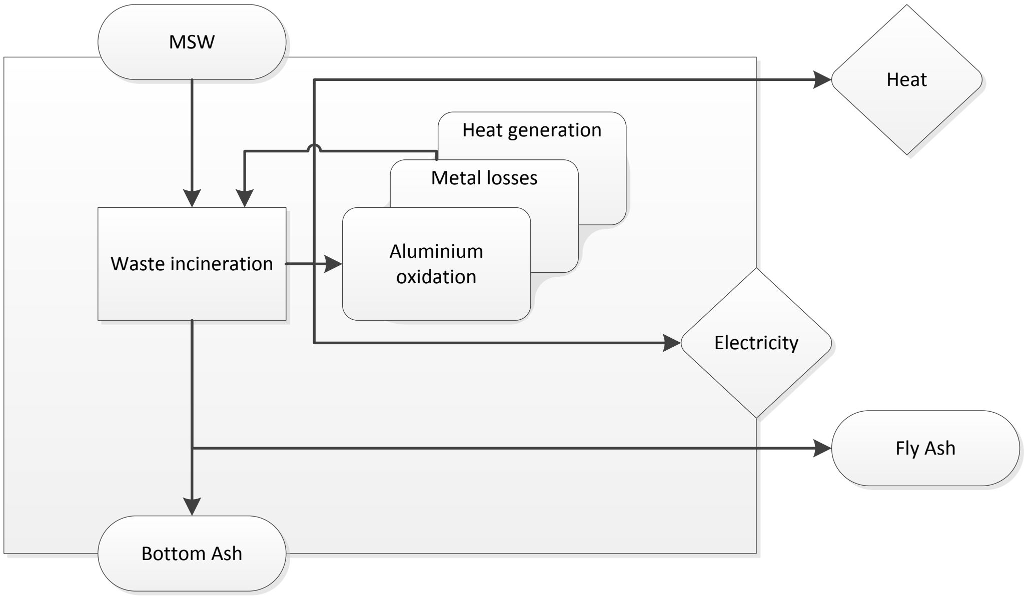

Figure 3: schematic overview of sub-system dealt with in chapter 3

3.2. Incineration process

The collected and in some cases pre-sorted "non-recyclable" waste is transported to the MSWIs by truck. From there the waste is introduced into a bunker, in which the consistency of the waste is, to some extent, homogenized with a crane. From the bunker the waste is fed into a funnel above the furnace, which is commonly a grate furnace in the Netherlands. A constant supply of waste on the grate in combination with a constant distribution of waste over the grate is important to ensure an even combustion. The grate can be divided into four zones, on which the combustion takes place. At the first zone the waste, which still contains water, will be dried. At the second zone the volatile matter will be evaporated after which the organic gasses will be ignited. At the third zone the solid mass will be combusted. On the last section the remaining ashes will anneal before they are quenched. The actual combustion takes place in the gas phase where the volatile organic gasses meet oxygen, combust, and thereby release energy. If the calorific value of the waste is high enough and other requirements, such as sufficient oxygen, are met, a chain reaction will start from which point a self-sustaining combustion is reached (European Commission, 2006). In most cases the grate is aligned with a slope in order to ease the transport of the waste throughout the furnace, together with moveable tiles or another way to homogenize the waste on the grate. Due to the semi-open structure and the funnels below the grate, part of the ashes fall off, the so called “through fall”. The aluminium found in the through fall seems to be less oxidized (Tauw, 2012). Both the ash streams will eventuality end up in the quencher in which they are rapidly cooled down with water. The quencher is not only used for cooling but also acts as an air lock, which prevents the access of tertiary air into the furnace which could disturb the combustion process. Oudenhoven (2014) states that, to a minor degree, the formation of hydrogen is observed in the quencher, which could be an indication of aluminium oxidation, which is also suggested by Biganzoli (2012). This will be discussed in paragraph 3.4. in more detail. Quenching has, according to Zwahr (2003) a beneficial effect, that reduces the salt concentration in bottom ash. Since part of the salts formed during the combustion dissolve into the quenching water, this increases the quality of the bottom ash. However the level of quality improvements depends on the amount of water which is refreshed. A simplified schematic overview of a MSWI is shown in figure 4.

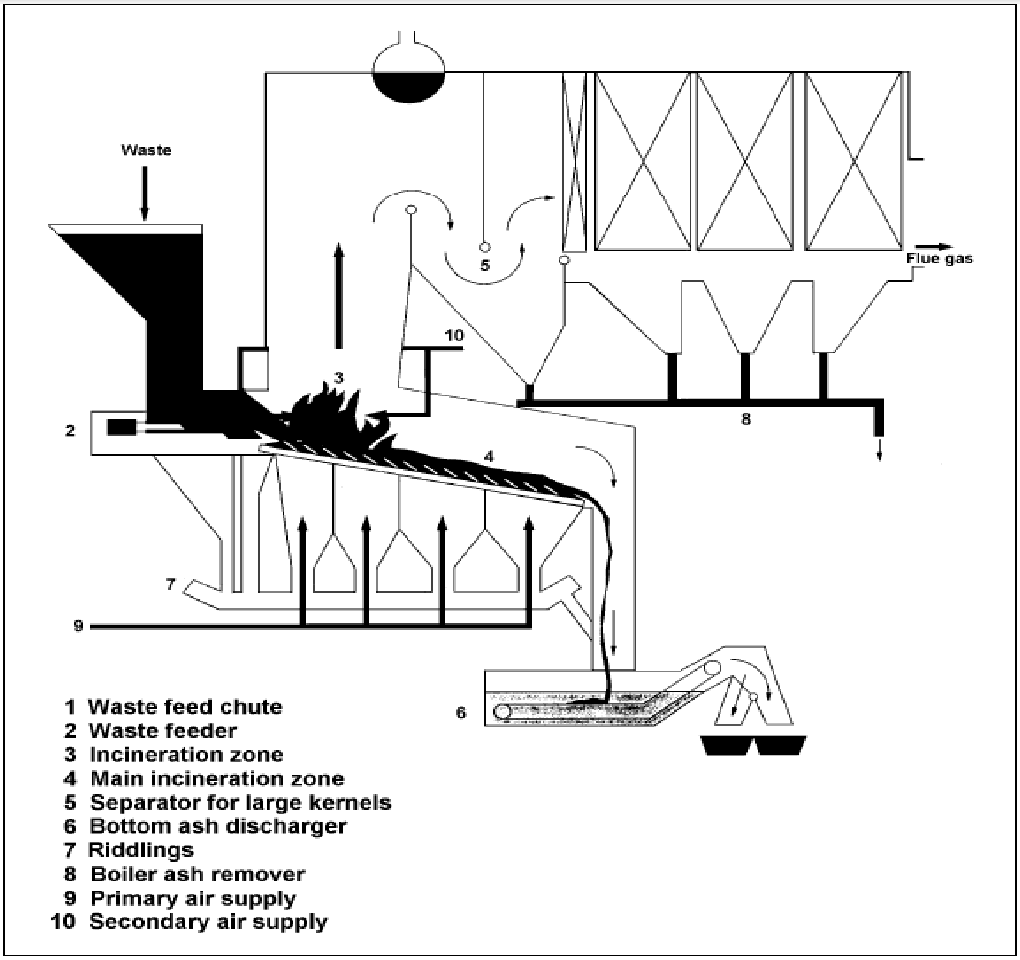

Figure 4: simplified schematic overview of an MSWI plant[2]

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[2] Source: European Commission (2006)

The funnels underneath the grate also allow the supply of oxygen rich air (primary air), which is required for the combustion of the waste. The exact oxygen concentration around the bottom ash however is hard to determine and therewith the rate of aluminium oxidation (Oudenhoven, 2014). Other factors, which influence the combustion rate, are the temperature and the residence time. These factors also influence the oxidation of aluminium. The temperature in the fire zone is between 800 and 1 000°C while the temperature of the re-combustion of the flue gas can reach temperatures up to 1 250°C (Janssen, 1999). The residence time of the waste can go up to 3 hours, from the feeding funnel until the deslagger (Tauw, 2012). In most cases the residence time on the grate is 0.75 to 1.5 hours (Janssen, 1999). The heat, which is generated due to the combustion, is used to make steam, to operate a turbine in order to generate electricity. Part of the remaining heat is, in most cases, used for district or industrial heating.

3.3. Aluminium in the incinerated waste

Aluminium, mostly in the form of alloys, is used in a high amount of consumer goods, such as beverage cans, foils, trays, aerosols, tubes, capsules and a wide range of thin laminated foil applications, such as wrappings, lids and pouches (EAA, 2013). These consumer goods and their aluminium end up in Municipal Solid Waste. The Dutch incinerators also combust Non-Process Related Industrial Waste (NPRIW) and mechanical sorted waste (a mixture of MSW and NPRIW), from which in some cases (larger pieces of) metals are partly removed, besides MSW and related waste. It is important to make a distinction between these streams since the amount of aluminium differs. The Dutch MSWIs also incinerate imported waste. In 2012 a total of 1 035 ktonne waste was imported and incinerated, according to Rijkswaterstaat (2013). No public data is available on the composition and the type of waste, in contrast to the Dutch waste. Therefore, the same ratio and composition is assumed for the imported waste. The amount of aluminium in different types of waste is hard to determine due to the heterogeneous character of waste. The data available is in most cases based on sorting tests and gives an indication of the amount of aluminium. Tauw (2012) estimates the amount of aluminium present in MSW at 0.8 % and estimates that no aluminium is present in NPRIW. SKB (2007) assesses the amount of aluminium in NPRIW at10 % of the amount in MSW. This is also assumed in this analysis. The amount of aluminium in sorted waste (Eural code 191212) and the extent to which aluminium is removed is not known. Therefore, the sorted waste is estimated to have an aluminium content of 0.3 %, which is based on the mixture of MSW and NPRIW. Considering these values, a total of 41.2 ktonne or 0.55 wt.% of the waste aluminium was incinerated in 2012. This is considered as an important input parameter since no exact data is available about the amount of aluminium in the total incinerated waste. An overview of the results is provided in table 1 and the full calculations can be found in Annex I.

Table 1: assessment of aluminium present in incinerated waste in 2012

Description:	Value:
Waste incinerated (ktonne)	7 471[3]
Imported waste (ktonne)	1 035[3]
Dutch waste (ktonne)	6 436[3]
MSW in incinerated Dutch waste	55 %[3]
NPRIW in incinerated Dutch waste	6 %[3]
Sorted waste in incinerated Dutch waste	36 %[3]
Aluminium concentration in Dutch MSW	0.8 %[4]
Aluminium concentration in Dutch NPRIW	0.08 %[5]
Aluminium concentration in Dutch sorted waste	0.3 %[6]
Aluminium concentration in imported MSW	0.8 %[7]
Aluminium concentration in imported NPRIW	0.08 %[7]
Aluminium concentration in imported sorted waste	0.3 %[7]
Aluminium in incinerated waste (ktonne)	**41.2**

3.4. Aluminium losses

During the incineration of waste several aluminium losses will occur, which will be examined in this paragraph.. The main losses during incineration are attributable to oxidation of aluminium, a small fraction to flue gas and fly ash. However, not much is known about the exact way losses occur in the incinerator. Hu, et al. (2011) and López, et al. (2013) performed laboratory scale research in which they describe the oxidation losses during incineration, while Biganzoli (2012) performed an industrial scale test for two MSWIs in Northern Italy. The comparability of this research with the Dutch situation is however uncertain (Oudenhoven, 2014). Tauw (2012) performed a test in the Netherlands on an industrial scale, which gives some additional insights. Much is still unknown since the circumstances for the different MSWIs vary. The heterogeneous character of waste, the variation of the composition over time and location also play a role. Nonetheless it is tried to assess and describe the losses based on the available literature in this paragraph.

Oxidation losses

Blanc aluminium and aluminium alloys will form a natural oxide layer with a thickness of 5 to 10 nm. Depending on the alloy composition the thickness of the oxide layer can vary (Kirk-Othmer, 1992). During the incineration of waste, aluminium particles will further oxidse, due to the presence of oxygen, higher temperatures and due to the abrasion of the existing oxide layer to eventually form aluminium oxide (Al_2O_3) (Biganzoli, 2012). Because of the high temperature in the furnace and the somewhat lower temperature on the grate, it is most likely that part of the aluminium will melt, since the melting point of aluminium is 660.2 °C (Kirk-Othmer, 1992). However, the temperature on the grate is not exactly known.

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[3] Data derived from Rijkswaterstaat (2013) with the assumption that the same ratio applies to imported waste
[4] Data derived from Tauw (2012)
[5] Data derived from SKB, as reported in Nedvang (2012)
[6] Assumption based on the fact that this is a mixture of MSW and NPRIW
[7] Assumption that this is similar to the composition in the Netherlands

Liquid aluminium is also able to form an oxide layer. Due to the movement of the waste on the grate the aluminium drops can be agitated and therefore become more prone to oxidation (Kirk-Othmer, 1992). At the same time the liquid phase provides a level of freedom to the aluminium, which allows some of the aluminium to seep through the waste on the grate itself to a zone where it is less exposed to the high temperature and agitation. This seems to have a positive effect on the oxidation grade (Tauw, 2012). This is most likely the case for larger aluminium particles since they are, due to their volume, harder to cool down and therefore more prone to leak through the grate.

The size of aluminium particles is an important contributing factor to the degree of oxidation. Research suggests that smaller aluminium particles are more prone to oxidation than larger particles (Hu, et al., 2011) (López, et al., 2013) (Biganzoli, 2012). This makes sense, since smaller particles have a relatively larger surface at which the oxidation occurs. Therefore, the total level of oxidation is higher for smaller particles. The thickness might also be an influence as stated by Hu, et al (2011) and Biganzoli (2012), but López, et al (2013) found no evidence for this. Thinner particles may form smaller droplets, which have a lager surface area, and therefore a higher degree of oxidation (Biganzoli, 2012). At the same time it could be that larger droplets are able to move over and under the grate and fall through to an area where the particles are less exposed (Oudenhoven, 2014). The oxidation process is further influenced by the harsh circumstances present in the furnace of the incinerator, such as the presence of salts (Hu, et al., 2011). The oxidation level also depends on the morphology and the composition of the aluminium items (Soler, et al., 2009). Aluminium alloys with a higher copper content can for example be more prone to corrosion, due to the fact that copper is less reactive than aluminium, which has a negative influence on the aluminium oxidation. However, this depends on the total composition of the alloy and not on a single element (Aluminium Centrum, 2000). A few examples of the chemical composition of typical aluminium alloys used in different consumer goods are shown in table 2.

Table 2: typical composition of aluminium alloys used for packaging[8]

Aluminium alloy number	8011	3004	3105
Application	Aluminium foil	Soda can	Soda Can
Chemical composition			
Aluminium, Al	97.3 - 98.9 %	95.5 - 98.2 %	≤ 95.9 %
Chromium, Cr	≤ 0.050 %	-	≤ 0.20 %
Copper, Cu	≤ 0.10 %	≤ 0.25 %	≤ 0.30 %
Iron, Fe	0.60 - 1.0 %	≤ 0.70 %	≤ 0.70 %
Magnesium, Mg	≤ 0.050 %	0.80 - 1.3 %	0.20 - 0.80 %
Manganese, Mn	≤ 0.20 %	1.0 - 1.5 %	0.30 - 0.80 %
Other, each	≤ 0.050 %	≤ 0.050 %	≤ 0.050 %
Other, total	≤ 0.15 %	≤ 0.15 %	≤ 0.15 %
Silicon, Si	0.50 - 0.90 %	≤ 0.30 %	≤ 0.60 %
Titanium, Ti	≤ 0.080 %	-	≤ 0.10 %
Zinc, Zn	≤ 0.10 %	≤ 0.25 %	≤ 0.40 %

Not only the high temperature can be a reason for accelerated oxidation rates, the rapid cooling due to the quenching of the bottom ash also promotes further oxidation of aluminium (Oudenhoven, 2014) (Biganzoli, 2012). This is caused, according to Biganzoli (2012), by a thermal shock which is introduced on the oxide scale around the aluminium particle. This scale could easily break loose and thereby further expose the metallic aluminium to oxidation in an aqueous environment according to equation 1.

Equation 1: the oxidation of aluminium by water

$$Al + 3H_2O \rightarrow Al(OH)_3 + \frac{3}{2}\,H_2$$

Due to high pH value of the bottom ash and reaction with water the remaining aluminium could be further oxidised,because the surface passivation of aluminium is reduced by the high pH-value (Biganzoli, 2012). In the following reactions the further oxidation of aluminium due to the presence of sodium hydroxide (equation 2) is shown. The reaction consumes sodium hydroxide until the saturation point of aluminate is reached, from which point the aluminate decomposes into sodium hydroxide and a crystalline precipitate from aluminium hydroxide (equation 3) (Biganzoli, 2012).

Equation 2: oxidation of aluminium by sodium hydroxide

$$2\,Al + 6H_2O + 2\,NaOH \;\rightarrow 2\,NaAl(OH)_4 + 3\,H_2$$

Equation 3: decomposition of aluminate

$$NaAl(OH)_4 \;\rightarrow NaOH + Al(OH)_3$$

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[8] Data derived from Matweb (2014)

According to Biganzoli (2012) the presence of hydroxide ions enhances the decomposition of the oxide layer (equation 4) and thereby promotes further oxidation.

Equation 4: further oxidation of aluminium

$$Al(OH)_3 + OH^- \leftrightarrow Al(OH)_4^-$$

Hydrogen gas is formed, as can be seen in the previous equations. The formation of hydrogen can lead, according to Ishii (2007), to stress corrosion, in which the hydrogen formation cracks the aluminium oxide layer and thereby opens it for further oxidation.

In the Netherlands bottom ash is, in most cases, stored for a few days, but storage times of two months also occur, to dewater the bottom ash (Tauw, 2012). The reason for this storage is to increase the treatability of the bottom ash and therewith the recoverability of non-ferrous metals. Due to the storage the oxidation of aluminium can be prolonged, according to the previous stated reactions, before the aluminium is recovered from the bottom ash. In contrast to the oxidation in the incinerator this does not contribute to the energy contribution, since this does not take place in the furnace as will be further discussed in the next paragraph. Factors influencing the oxidation, besides the storage time, are the temperature, which could be from 40°C up to 90°C, the pH-value and salt concentration in the bottom ash. A smaller diameter of particles also seems to have a negative impact on the oxidation during storage (Tauw, 2012). Most of the losses occur within the fine fraction (0-2 mm) with a loss of 10 % observed in a storage period of 3 weeks. While the overall loss for the bottom ash is estimated at a few percent (Tauw, 2012), this hardly affects the recoverability of aluminium, since the small particles cannot yet be recovered with the existing technology.

As stated before, Hu, et al. (2011) performed a laboratory test in which the oxidation level of aluminium in MSW was determined (including quenching). This was done for several types of consumer products, namely: aluminium thin foil, foil containers and cans. It was concluded that the recovery factors for metallic aluminium were respectively 77, 88 and 93 wt.%. Factors such as higher combustion temperature, longer residence time, other pH-value and higher salt contamination, have a negative effect on the recovery factor.

The distribution of aluminium over the bottom ash size fractions is also an important factor, since the recovery over these factors varies . This is mainly determined by the type of packaging and only moderately by the input shape (crumbled or not). According to Hu, et al (2011), 70 % of the metallic aluminium from cans ends up in the >6 mm bottom ash fraction with 45 % of the containers metallic aluminium. This in contrast to the thin foil, which metallic aluminium ends up for 43 wt.% in the <2 mm bottom ash fraction. This shows that the size distribution is an important factor for the further recoverability of the aluminium. Further details of the size distribution can been found in figure 5.

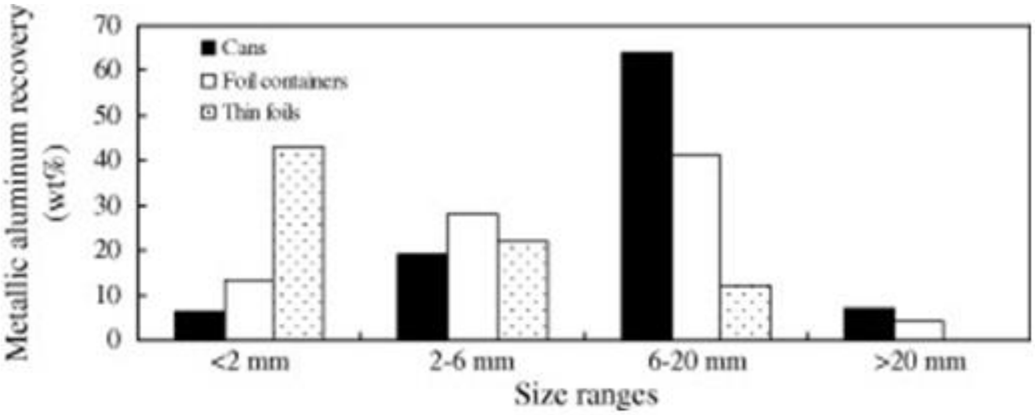

Figure 5: metallic aluminium recovery and size distribution in MSWI bottom ash originated from different consumer articles [9]

Results from other publication give a mixed view. While some particles show an oxidation grade up to 60 %, according to Buekens in 1993 (Pruvost, 2011), López, et al. (2013) reports considerably lower oxidation values from a lab scale expiriment where the oxidation differs also per kind of packaging material which are shown in table 3.

Table 3: aluminium transformed into AL_2O_3 [10]

Packaging format	Aluminium oxidation into Al_2O_3 (wt.%)
Semi-rigid	0.8 ± 0.6
Flexible A[a]	3.9 ± 6.4
Flexible B[b]	9.4 ± 9.9

[a] Low Al content [b] High Al content

Grosso (2011) conducted an industrial test and reported an avarage loss of mass of 41.3 wt.%. Bigonzoli did a more extensive study into the diffrent kinds of packaging material and the influence of thickness. The results are shown in figure 6. Bigonzoli acknowledged the fact that the plant design has some influence on the oxidation. The residence time also seems longer than in the Netherlands, with the time from feeding the MSW into the furnace until sampling being 9-10 hours in Piacenza and 4-6 hours in Valmadrera. These factors can lead to a higher oxidation in Piacenza, according to Biganzoli (2012). Comparing this to the Dutch situation, where the oxidation rate is lower according to Tauw (2012), is rather hard, since the ammount of variables is high. It could be explained by the longer residence time, the type of furnace, the tickness of the waste on the grate, the temperature and oxygen concentration of primary air and at the bottom ash level of the furnace (Oudenhoven, 2014). Nonetheless, the results presented in figure 6, which show a diffrence in the oxidation, are useful for more insight in what happens with aluminium in the furnace for this reserach.

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[9] Source Hu, et al. (2011)

[10] Source: López, et al. (2013)

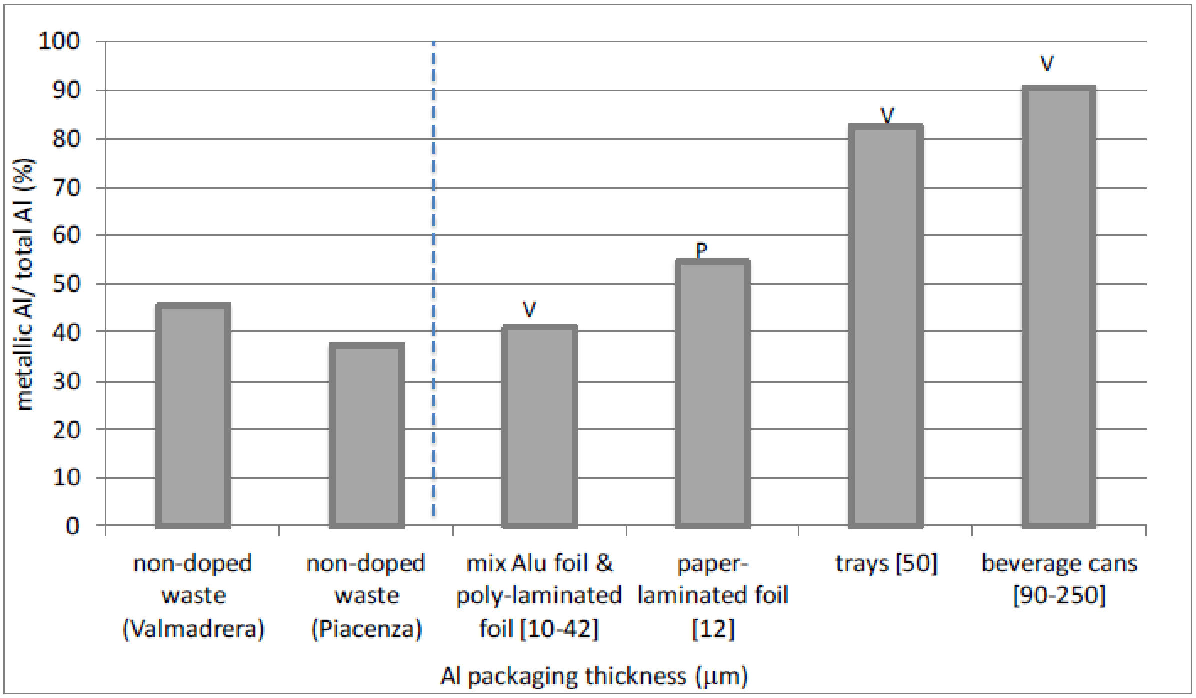

Figure 6: relation between packaging thickness and aluminium oxidation[11]

In the cases of López, et al. (2013) & Biganzoli (2012) the aluminium is less oxidised if protected by other layers such as paper or PE. These cases show that the level of oxidation depends on multiple variables regarding the packaging material, but also the circumstances in the incinerator. Acording to Tauw (2012) the overall loss in recoverable mass is 10-20 % due to oxidation in the process for the Netherlands.

Comparing this value with other research, especially the results from Biganzoli (2012) and Buekens (Pruvost, 2011), it seems somewhat low, and they are more in line with the lab experiment from Hu, et al. (2011). However, it must be noted that this represents an overall oxidation grade in which aluminium foil may have a higher oxidation grade, but also contains less aluminium than heavier consumer goods, such as trays and beverage cans which makes an overall oxidation grade of 10-20 % more likely.

Energy generation due to oxidation of aluminium

The oxidation of metallic aluminium is, in a material sense, considered a loss. At the same time this oxidation can, just as regular combustion, generate energy. According to the CEN standard on energy recovery (EN 13431:2004), thin gauge aluminium foil with a thickness up to 50 µm is to be considered completely oxidisable and thereby generating energy while incinerated. This is however challenged by Biganzoli (2012), where only 50 % of the aluminium foil was oxidised. About the actual reaction kinetics, which occur during the oxidation of aluminium, much is still unknown (Doremus, 2004). The net reaction, which occurs, is given in equation 5.

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[11] Source: Biganzoli (2012)

Equation 5: Overall reaction of aluminium oxidation and generation of energy

$$4\ \mathrm{Al}_{(s)} + 3\ \mathrm{O}_{2\,(g)} \rightarrow 2\mathrm{Al}_2\mathrm{O}_{3\,(s)} \qquad \Delta \mathrm{H}_f^{\circ}(298) = -1\ 675.7\ kJ/mol$$

A large amount of energy is released when aluminium forms aluminium oxide. This is due to the fact that a crystal lattice is formed because of strong ionic bonding of gaseous ionized aluminium and oxygen (equation 6). This results in the release of 31.05 MJ/kg (CRC, 2013) of energy, when aluminium is oxidized by oxygen in the combustion air, at temperatures above 850°C. However, as Biganzoli (2012) discribed, this is under the assumption that aluminium is not reacted in other minerals such as ettringite, zeolites or other alumino-calcium hydrate compounds. This influences the amount of energy released by the oxidation. In the case study performed by Biganzoli (2012) the contribution of energy could be up to 1 % of the total energy generated in the furnace of the MSWI.

Equation 6: ionic bonding of ionized aluminium and oxygen into aluminium oxide

$$2\ Al^{3+}{}_{(g)} + 3\ O^{2-}{}_{(g)} \rightarrow 2\ \mathrm{Al}_2\mathrm{O}_{3\,(s)}$$

Aluminium is not only able to oxidize with oxygen in the combustion air but also with metal oxides (known as Goldschmidt reactions), such as iron oxide, as can be seen in equation 7. For the calculation of energy, equation 5 will be considered, since a reaction with oxygen from the combustion air is more likely than a reaction with metal oxides, since compared with metal oxides, oxygen is abundantly available.

Equation 7: reduction of iron oxide by aluminium (New Mexico Tech, 2013)

$$2\ Al_{(s)} + Fe_2O_{3\,(s)} \rightarrow 2\ \mathrm{Al}_2\mathrm{O}_{3\,(s)} + 2\ Fe_{(s)} \qquad \Delta \mathrm{H}_f^{\circ}(298) = -851.5\ kJ/mol$$

Losses to fly ash

In the case of losses to fly ash it is most likely that thinner aluminium particles will volatise during incineration or will be carried out of the incinerator with the flue gas. After cooling of the flue gas the aluminium will mainly attach to the surface of fly ash (also known as APC residue). This could be either in metallic or oxide form (Biganzoli, et al., 2012). In table 4 the vapour pressure and the rate of evaporation and erosion are shown to give an impression of the effect a temperature increase has on pure aluminium.

Table 4: vapour pressure, evaporation and erosion rate of pure aluminium as a function of the temperature[12]

Temperature	Vapour pressure	Evaporation/Subl. Rate	Erosion
T(°C)	P (mbar)	(atoms/m^2s	(m/s)
0	1.11E-53	3.40E-29	0.00
100	8.94E-37	2.30E-12	3.90E-41
200	4.92E-27	0.011	1.90E-31
300	1.05E-20	2.20E+04	3.70E-25
400	2.89E-16	5.60E+08	9.40E-21
500	5.56E-13	1.00E+12	1.70E-17
600	1.87E-10	3.20E+14	5.30E-15
700	1.81E-08	2.90E+16	4.90E-13
800	6.47E-07	1.00E+18	1.70E-11
900	1.25E-05	1.90E+19	3.10E-10
1000	1.53E-04	2.20E+20	3.60E-09
1100	1.29E-03	1.80E+21	2.90E-08

According to a model from Arena & Di Gregorio (2013) an average MSWI, which contains 1 wt.% aluminium in the wet feedstock, divides the aluminium, with 90 wt.% into the bottom ash and 10 wt.% to the fly ash. The flue gas contains, after cleaning, 2.6x 10^{-3} wt.% aluminium and can therefore be considered negligible. However, these data may vary over different MSWIs due to the different composition of the waste or different operation parameters. The majority of the aluminium in the flue gas is aluminium oxide, but the exact ratio between metallic and aluminium oxide is not discussed in this paper. In flue gas and fly ash it is most likely that, since they are relatively small, these particles have a high oxidation grade. In any case the amount of metallic aluminium, which is attached to the fly ash, can be seen as a loss of material since this is not recoverable with current techniques. According to Oudenhoven (2014), the amount of metallic aluminium, which is transferred to fly ash, is most likely lower than the calculated 10 %. This is confirmed by Tauw (2012), where 0.2 wt.% of the input aluminium turns up as metallic aluminium in fly ash. These values do not contradict each other since the remainder of the aluminium, is aluminium oxide. Therefore, the losses must be seen as an oxidation loss instead of direct metal losses to fly ash.

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[12] Data derived from TU Wien (2013)

Aluminium accumulation

Besides the previous stated losses, there is also the possibility of aluminium accumulation in the furnace. This is caused by the fact that aluminium melts in the waste and seeps through the grate, under which the temperature is considerably lower, which solidifies the aluminium. A part of the aluminium can solidify on the surface of the plant (Tauw, 2012). Due to the movement of (tiles on) the grate, part of this aluminium ends up in the bottom ash the remaining aluminium is removed during an overhaul of the incinerator. As stated before the aluminium present in the through fall has a lower oxidation grade than the normal bottom ash. It is unknown what the level of oxidation is for the accumulated aluminium, and it is also unclear to what extend aluminium accumulates beneath the furnace. However, the accumulated metals are recovered during the overhaul and, together with the recovered metals from bottom ash, treated further (Oudenhoven, 2014).

3.5. Aluminium losses and energy recovery

Aluminium oxidises, as described in paragraph 3.4., will lead to losses in metallic aluminium recovery and at the same time will contribute to the generation of energy, as the oxidation occurs in the furnace. Since the oxidation of aluminium depends on several variables, such as type of furnace and type of packing material, an overall oxidation grade is used for the Netherlands. Tauw (2012) reports an overall loss of aluminium of 10-20 wt.% due to oxidation. At the same time 0.2 wt.% of the metallic aluminium input is lost as metal to the fly ash. Since most Dutch MSWIs store the bottom ash, the oxidation continues outside the furnace and therefore does not contribute to the energy generated at the MSWI. According to Tauw (2012) this oxidation mainly takes place in the <2 mm fraction, with an oxidation of approximately 10 %. Since the <2 mm contributes more than 20 % of the total mass (23 % was used in this analysis, a total of 0.96 ktonne is further oxidised without contributing to the energy generated in the MSWI. This means that the total of recoverable aluminium is assessed at 34.0 ktonne for 2012. The oxidation, as indicated, will lead to the additional recovery of energy. In order to calculate the contribution of the aluminium oxidation to the total of energy generated, it is necessary to know the calorific value of waste. The average calorific value of the Dutch waste is annually calculated according to Rijkswaterstaat (2013) and this was 9.6 MJ/kg for 2011 (Agentschap NL, 2013). This is based on sorting analysis in which the amount of waste in standard categories, such as paper and plastics, is multiplied with their specific calorific value. In practise this value could range from 8.5 up to 14 MJ/kg for waste, that is incinerated. The 9.6 MJ/kg however is the best average value available.

Based on this average calorific value the total amount of energy, which is being released during combustion, is calculated. Given the energy release of the oxidation of aluminium, which is according to the Handbook of Chemistry and Physics (2013) 31.05 MJ/kg, the additional energy contribution of the oxidation is 0.19 PJ, which corresponds to 0.27 % of the total amount of energy released. This amount of energy is generated additionally, since Rijkswaterstaat (2013) assumes no calorific value for non-ferrous metals.

Comparing this value with the results from Biganzoli (2012), where the contribution of energy due to the oxidation of aluminium was above 1 %, the contribution is considerably lower. This could be explained by the lower oxidation grade in the Netherlands compared to the one in Italy (Biganzoli, 2012), as is discussed in 3.4.. The results of this analysis are presented in table 5; the complete calculation can be found in Annex I.

Table 5: assessment of the potential recovery and energy contribution of aluminium

Description:	Value:
Aluminium in incinerated waste (ktonne)	41.2
Overall oxidation grade	15 %[13]
Aluminium oxidized in the furnace (ktonne)	6.2
Mass fraction aluminium to fly ash (m/m)	0.20 %[13]
Aluminium to fly ash (ktonne)	0.1
Mass fraction aluminium 0-2 mm	23 %[14]
Aluminium oxidised 0-2 mm	10 %[13]
Aluminium oxidised outside the furnace (ktonne)	0.96
Potential recoverable aluminium (ktonne)	**34.0**
Waste incinerated (ktonne)	7 471[15]
Average calorific value waste MJ/kg	9.6[16]
Total energy released (PJ)	72
$\Delta_c H^0$ Al--> Al_2O_3 (MJ/kg)	31.05[17]
Additional energy contribution due to oxidation (PJ)	**0.19**
Energy contribution oxidation	**0.27 %**

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[13] Data derived from Tauw (2012)
[14] Data derived from TU Delft (2013) and Muchova (2010)
[15] Data derived from Rijkswaterstaat (2013)
[16] Data derived from Agentschap NL (2013) data is for 2011
[17] Data derived from CRC, Handbook of Chemistry and Physics (2013)

3.6. Conclusion

This chapter described the incineration of Municipal Solid Waste and the relevant processes that affects the amount of metallic aluminium in it. The analysis shows that an amount of 41.2 ktonne (0.55 wt. % of the incinerated waste) of metallic aluminium is present in MSW, of which 6.2 ktonne is oxidized in the furnace, while an additional amount is lost to fly ash or oxidized outside the furnace (respectively 0.1 and 0.96 ktonne). This leaves 34.0 ktonne in the bottom ash to potentially be recovered. The oxidation of aluminium to aluminium oxide within the furnace contributes with 0.19 PJ on top of the energy released by the combustion of waste, with 0.27 % of the total energy released. This is also presented in figure 7.

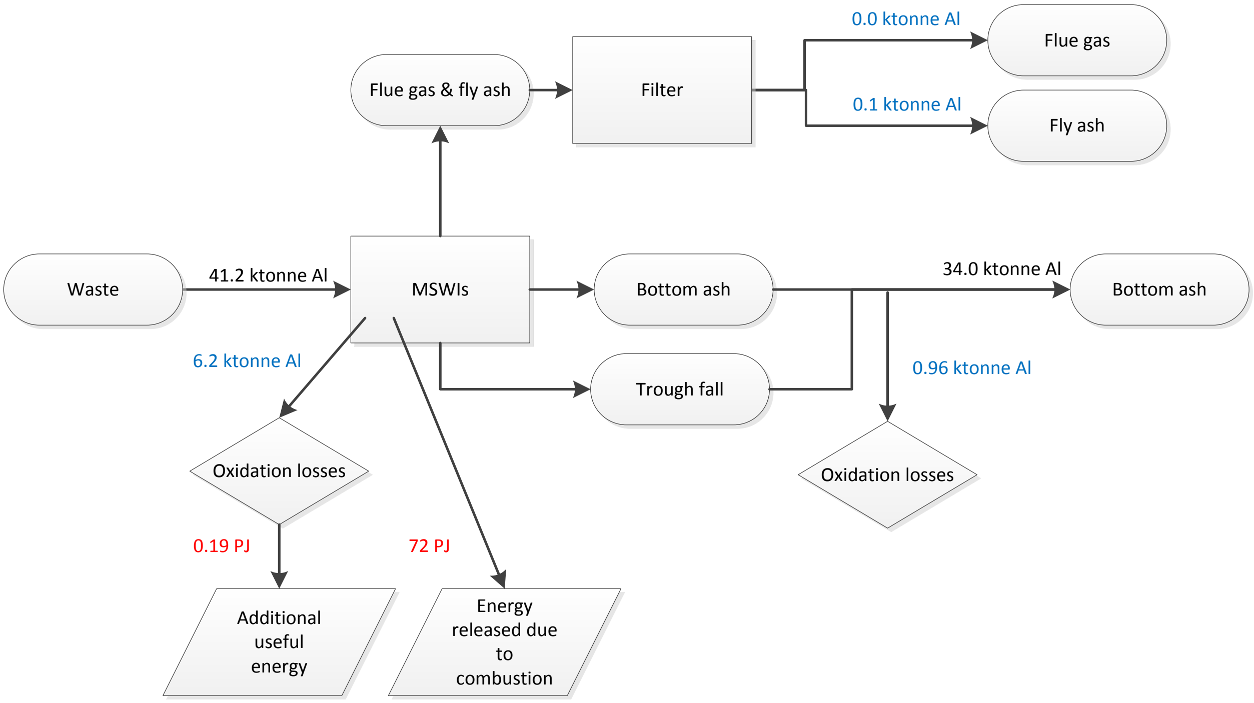

Figure 7: overview of the incineration of waste and its effect on aluminium

Chapter 4: Aluminium recovery from bottom ash

4.1 Introduction

The recovery of non-ferrous metals from bottom ash in within the Netherlands in 2012 is, in most cases, performed with standard dry recovery techniques. Recent developments, such as Advanced Dry Recovery and wet separation, can increase the recovery of non- ferrous metals. In this chapter the general technology and the recent developments will be described. An evaluation is made of their pros and cons, in order to determine the best available technology for the Netherlands. Furthermore, an analysis will be performed to determine the recovery factors of the sub-system as is described in figure 8, as well as for the entire system dealt with until now. Moreover, the impact of these technologies on the quality of bottom ash is analysed, in order to make an assessment of the allocation of energy to the different product streams. The energy usage for internal and external transportation is also considered. Based on these values the energy requirement for the recovery of aluminium is determined in this chapter.

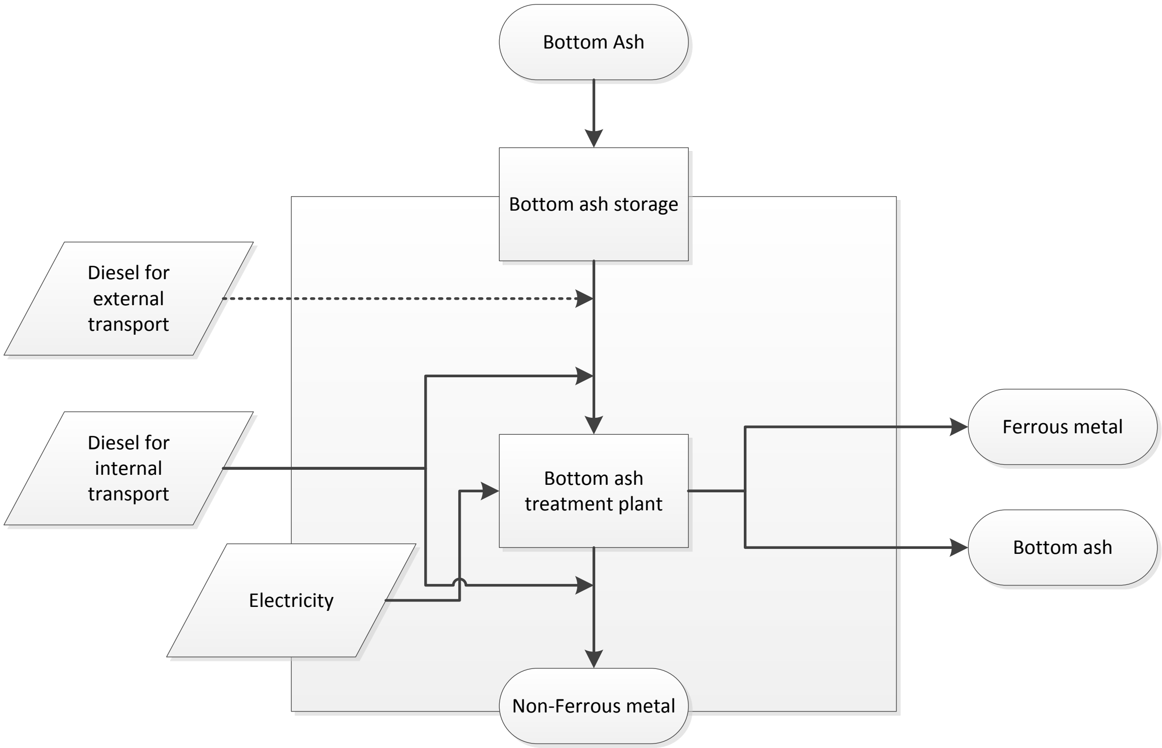

Figure 8: schematic overview of the sub-system dealt with in chapter 4

4.2. Bottom treatment plants in the Netherlands

In the Netherlands, bottom ash is always quenched as it leaves the incinerator (Berkhout, et al., 2011) (Tauw, 2012). This quenching increases the moisture content of the bottom ash, which leads to more problems with the further treatability and can increase the level of oxidation as is discussed in the previous chapter. The smaller sized (< 8 mm) bottom ash particles especially encounter water bridge formations, which makes it harder to recover valuable metals (Muchova, 2010). This is further specified by De Vries, et al. (2009), who state that the fines (< 2 mm) in the bottom ash make the entire fraction of 0-12 mm sticky and therefore hard to process. A lower processability affects the recovery of the non-ferrous metals. In order to extract these metals, the bottom ash could be dried (aging) to increase the processability, and therefore the recoverability. This, however, has as downside that the metallic aluminium content could decrease by oxidation during the ageing period with, according to De Vries, et al. (2009), up to 6.9 kg per tonne of bottom ash in a period of 10 weeks. Other authors have some doubts regarding the test conditions (Tauw, 2012), and expect a somewhat lower metal loss. Besides the enhanced oxidation due to aging, it could also affect the recoverability because small bottom ash particles stick together with small aluminium particles and are therefore harder to separate (Tauw, 2012).

After quenching the bottom ash, the physical separation starts. This includes sizing and the separations of specific fractions, such as non-ferrous metals (Biganzoli, 2012). Sizing is, according to Biganzoli, fundamental in order to isolate the more contaminated fine fractions and thereby upgrading the quality of the remaining stream. It also improves the recovery of metals from the different streams. Since equipment such as an Eddy Current Separator (ECS) can be calibrated and fine-tuned to a specific particle range, it can increase the recovery of non-ferrous metals.

Some MSWIs in the Netherlands use their own bottom ash treatment facility, while other incinerators combine their bottom ash streams at a central treatment plant. Most bottom ash treatment plants use a shredder circuit to reduce the size of the bottom ash to <40 mm. This also increases the recoverability of aluminium, since aluminium can sinter together with bottom ash particles (Tauw, 2012) and therefore could be harder to recover. Large organic pieces, which are not fully combusted, are fed back into the incinerator and large steel scrap is removed with magnets. Some plants also use an ECS to remove larger pieces of non-ferrous metals from the bottom ash (Rem, et al., 2004).

Since the ECS is the device that actually separates the non-ferrous metals from the bottom ash stream, some additional research is done into the principal of this technology related to the recovery of non-ferrous metals from bottom ash.

Eddy Current Separator

Non-ferrous metals, such as aluminium and copper, are removed from the <40 mm bottom ash by Eddy Current Separators. A standard ECS is basically a conveyer belt, where at the end of the belt non-ferrous metals are repelled from the inert bottom ash, which is not effected by the eddy currents.. This repelling is caused by a variable magnetic flux, which is caused by an electrical conductor surrounded by permanent magnets in the head pulley of the conveyer belt. By moving these magnets around the conductor this magnetic flux varies. The change in the magnetic flux causes the forming of a magnetic field around the non-ferrous particles. This interaction between the two magnetic fields causes the repelling of the non-ferrous particles from the conveyer belt (Biganzoli, 2012). The repelling effect depends on the mass, shape and the conductivity of the materials. Theoretically, an additional separation could be made between aluminium and copper, since aluminium has a lower specific gravity than copper and a higher conductivity. (Settimo, et al., 2004). However, this is not done in practice since the variable mass and shape of the particles a limiting factor.

In order to maximise the recovery of non-ferrous metals from bottom ash, multiple ECS devices are placed in sequence. Additionally, there are especially dedicated ECS devices, which are calibrated for the size of different bottom ash fractions. A basic schematic overview of an ECS can be found in figure 9.

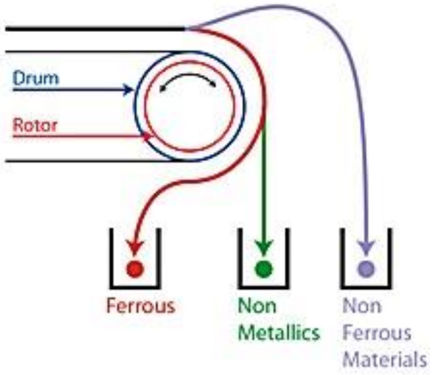

Figure 9: schematic overview of an ECS[18]

The principal of Eddy Current Separation can be used in different applications, such as:

- Wet Eddy Current Separation, which combines magnetic force and the lift force of water for the separation of non-ferrous metals, which can be up to a particle size of 0.5 mm (Nijhof & Rem, 1999)
- Magnus Eddy Current Separation, in which the Magnus effect is used to separate non-ferrous particles in a particle range from 1-10 mm from a bulks stream (Fraunholcz, et al., 2002)
- Backwards operating ECS, in which the magnetic rotor spins in the opposite direction as the drum. This has, according to Zhang, et al. (1998), a positive effect on the separation of particles smaller than 5 mm.
- A combination of these techniques can also be used to recover aluminium and other non-ferrous metals.

Non-ferrous metal recovery from bottom ash

According to Hu, et al. (2010), there are basically two types of non-ferrous metal recovery from bottom ash: Dry and Wet separation. Common dry separation is mostly applied in Europe, but more advanced technologies are being developed and applied. Since 2004, Wet separation is innovated by Rem for bottom ash application and trials have been performed at the Amsterdam and Alkmaar MSWI. In 2008, InAshCo introduced Advanced Dry Recovery, and this process is now applied at several bottom ash treatment facilities at a commercial scale. In Switzerland, actual dry treatment, which means without the use of a quencher, is applied since 2007 (Meylan & Spoerri, 2014).

These systems use several techniques such as dry or wet screening; wind sifting, jigging, LIMS and ECS. The configuration of these systems and the used techniques differ between the different forms and MSWIs, but the target in all cases is to separate the different fractions to treat the bottom ash and

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[18] Source: Buntingmagnetics (2013)

recover valuable materials (Hu, et al., 2010). However, the focus area may differ between the systems (Kok, 2014). The differences in configuration also imply differences in recovery, because they can have an economic and environmental impact. Therefore, a closer examination of the systems is performed.

Standard dry recovery

The standard dry recovery system is able to recover steel, coarse aluminium, and copper alloys from the bottom ash in a particle range from 10 to 40 mm with ECS (Hu, et al., 2010). In some cases bottom ash streams from > 6 mm were treated with reasonable efficiency, according to Oudenhoven (2014). The smaller bottom ash stream was not treated in this process, which is a drawback since this fraction also contains non-ferrous metals, and therefore the recovery factor of non-ferrous is reduced (Hu, et al., 2010). A schematic overview of a standard dry recovery system is shown in figure 10. Looking at the current bottom ash treatment plants, the difference in performance stands out as can be seen in Annex III, with an estimated aluminium recovery varying from 8-45%.

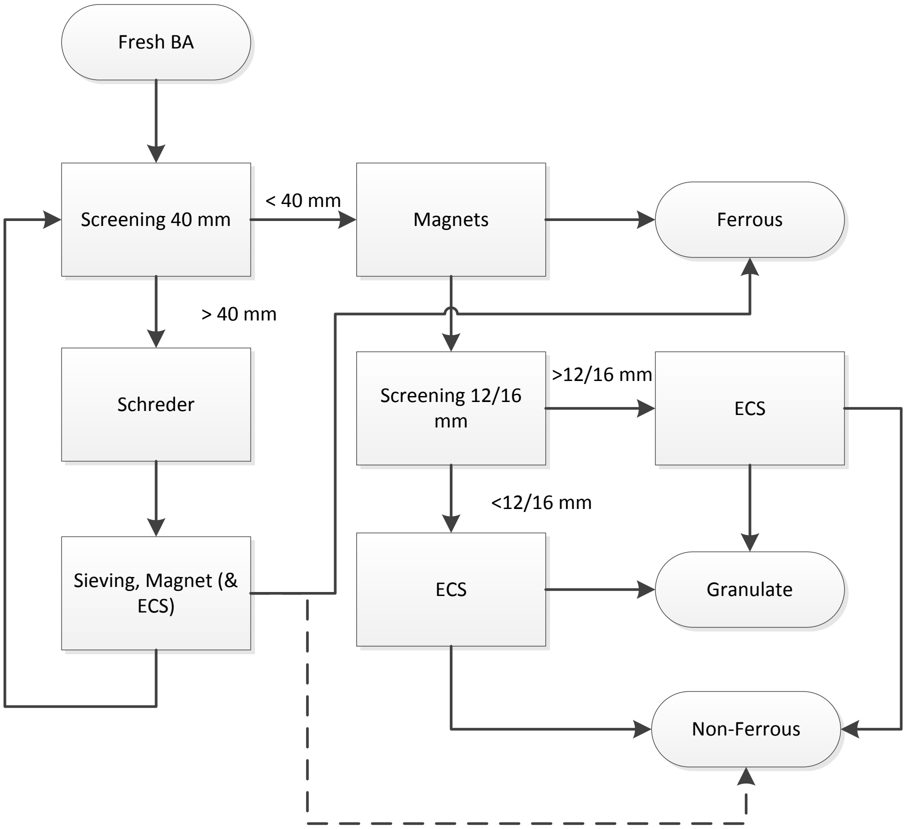

Figure 10: schematic overview of a standard dry recovery bottom ash treatment plant

Wet treatment

The wet separation system screens the ash with water in several fractions (<0,1 mm, 0,1-2 mm, 2-6 mm, 6-20 mm and 20-40 mm), in which the smallest fraction is treated by cyclones to separate the sludge. Therefore, this system is able to treat the fines up to 100 µm. Each fraction is treated individually and non-ferrous metals are recovered from the bottom ash streams with a particle size of 2 mm and larger (Hu, et al., 2010). According to Bakker, et al. (2007), the recovery of non-ferrous metals could reach

80-85 %. Wet treatment has as advantage that it washes out the solvable (in)organic content from the ash and removes the more contaminated fines from the granulate, which thereby improves the quality of the bottom ash (Muchova, 2010) (KEMA, 2011). Since the contamination could sinter together with the bottom ash and ferrous metal particles (Deike, et al., 2012), the removal of the contamination is more likely to succeed under wet than dry circumstances. According to KEMA (2011), the efficiency of the wet treatment for removal of impurities depends on the amount of water used. This is very likely, since the limiting factor is the solubility of these salts in water. The wet process has as negative side effect that it produces sludge, which has no useful application at this moment and therefore has to be dewatered and landfilled. Furthermore, the salt concentration of the waste water is especially a problem for the MSWIs in the east of the Netherlands, since they are not allowed to discharge the water in contrast with the more western located MSWIs, where the water is more brackish, which has an effect on the discharge limits. This makes wet treatment uneconomical for some MSWIs in the Netherlands (KEMA, 2011) (Oudenhoven, 2014). According to Muchova (2010), especially the recovery of copper and other precious metals increases with this system (aluminium is not reported), compared with conventional techniques. Several test were performed with wet treatment but it is still considered as pilot scale technology (Steketee, et al., 2011) (Van Brand, 2013). Until now wet treatment of bottom ash is only being applied as a standalone unit, but this can also be integrated directly after the quencher (KEMA, 2011) (Kok, 2014).

A schematic overview of how a wet treatment could be implemented in a bottom ash treatment plant can be found in figure 11.

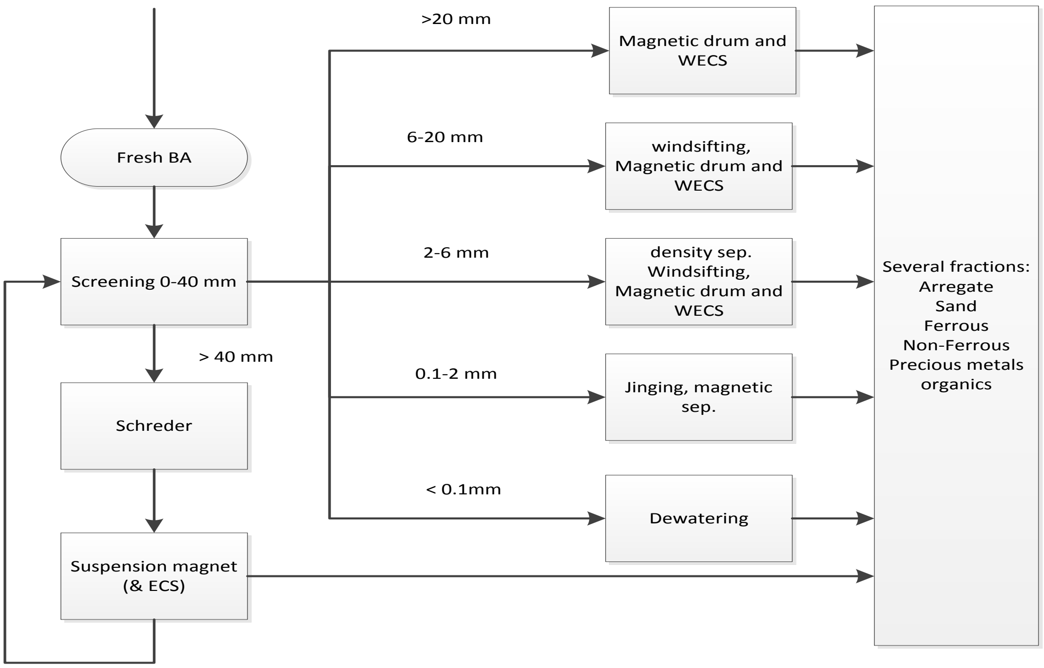

Figure 11: schematic overview of an bottom ash treatment plant supplemented with wet treatment plant[19]

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[19] Based on Muchova, et al. (2009)

ADR

Advanced Dry Recovery is a technology, which allows the separation of fine bottom ash particles (< 2 mm) from the remaining bottom ash (2-12/16 mm) and is used as an addition to the standard dry recovery. Since it is able to treat bottom ashes with a moisture content up to 20 wt.% (Bakker, et al., 2007), it allows the early processing of bottom ash, which should prevent the (further) oxidation of aluminium and thereby increases the recovery of aluminium. ADR technology uses kinetic energy to break the water bridges, which are formed by the water and fines (<2 mm) (De Vries, et al., 2009). Therefore, it is able to shift mineral particles with a size of < 2 mm from the bottom ash (Hu, et al., 2010). The fine fraction can be used as a product for the cement industry, while the bottom ash can be used in the concrete industry (De Vries, et al., 2009). The addition of ADR technology with dedicated ECS, achieves a higher recovery of non- ferrous metals than can be achieved with regular dry recovery. A schematic overview of how ADR may be applied in addition to other techniques is shown in figure 12.

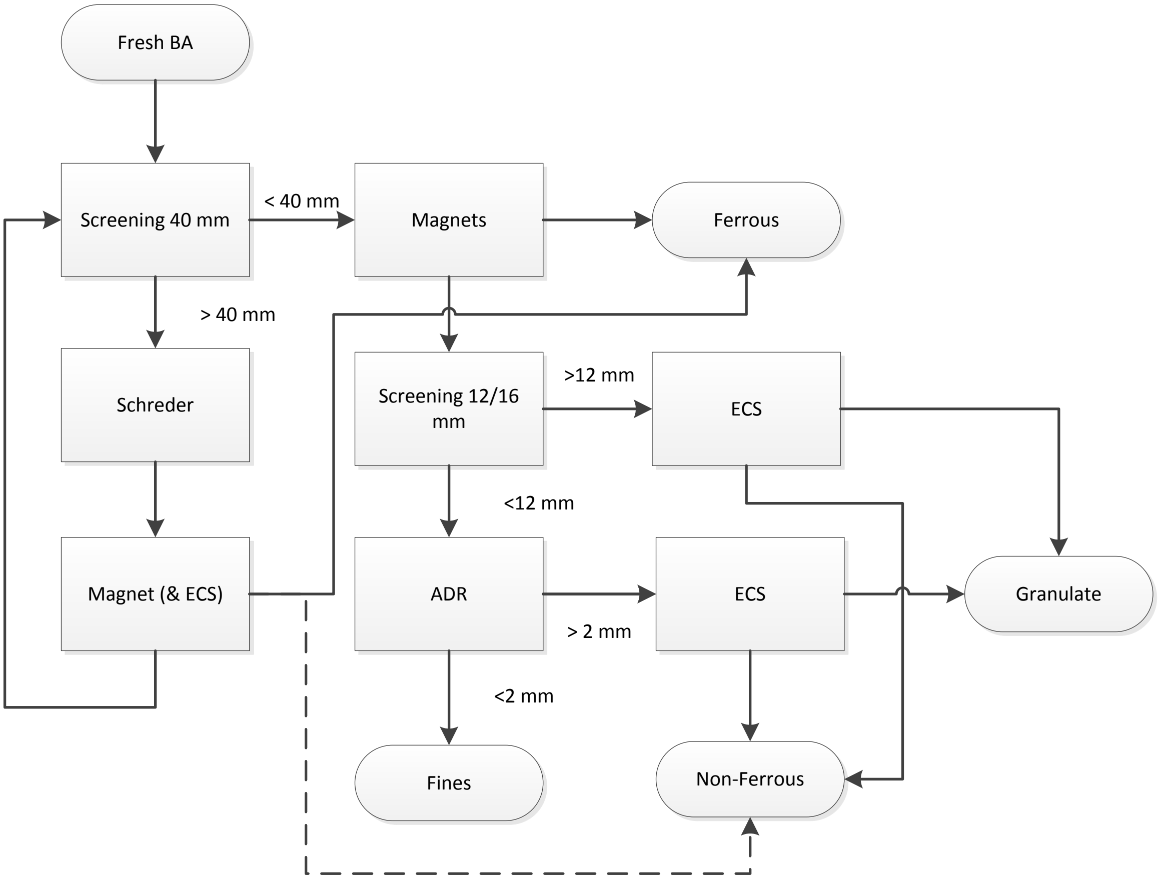

Figure 12: schematic overview of an bottom ash treatment plant supplemented with an ADR

Dry processing of bottom ash

A recent development in the treatment of bottom ash is the dry recovery of bottom ash from the furnace, as is currently applied at the Swiss Hinwil and Monthey waste incinerators. This is actually not a recovery technique, but a change in the incineration technique, where the bottom ash is not cooled down very fast with water, but gradually cooled down by air (KEMA, 2011). Applying this could increase the recoverability of aluminium since it allows the dry treatment of bottom ash down to 0.2 mm, which increases the treatable amount of bottom ash and also excludes the oxidation of aluminium during quenching and storage of the bottom ash. A non-ferrous metal recovery factor, for the 0.7-5 mm fraction, of 90 % is reported and still improvements are expected (Tauw, 2012). Therefore, this system is potentially the most favourable for the recovery of aluminium. For the Netherlands, a change to a dry deslagger corresponds with additional investments and major changes in the design of the incinerators. Therefore, it is unlikely that on a short term this system will be applied in the Netherlands. In figure 13 the outline of the dry bottom ash treatment is shown.

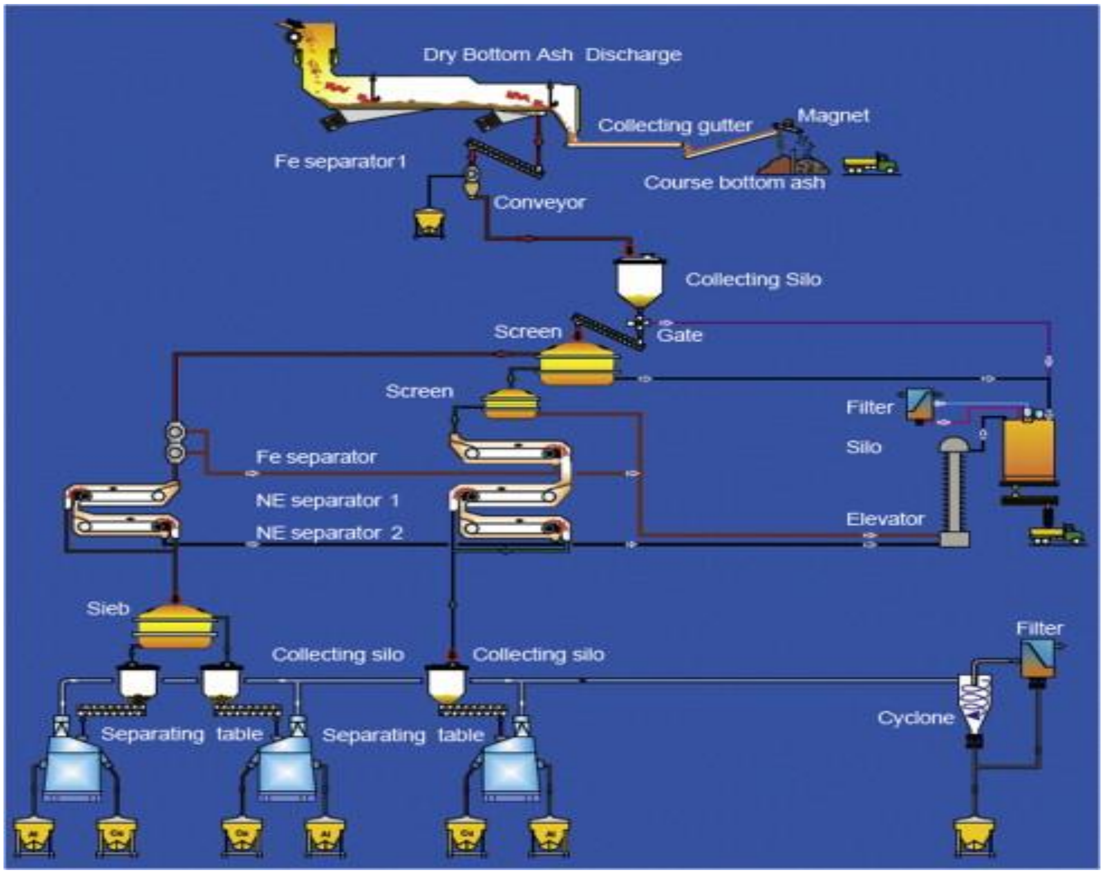

Figure 13: dry bottom ash treatment at Hinwil waste incineration[20]

Additional details of the aluminium recovery from bottom ash as reported in literature are displayed in Annex II.

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[20] Source: Meylan & Spoerri (2014)

4.3. Aluminium recovered from bottom ash

According to the DWMA (2013) the amount of clean non-ferrous metals recovered from bottom ash is 25.2 ktonne; the details can be found in Annex III. Clean non-ferrous means, that the impurities, such as organics, are deducted from the total mass. Based on data from several experts in the field, an estimate was made to determine the aluminium content of the recovered non-ferrous metals. These values can be found in Annex III. Based on their values the assumption was made, that the aluminium content in the non-ferrous fraction is 60 %. Since not only clean aluminium is removed but also some impurities an impurity factor of 10 % is used. Therefore, the aluminium content in clean non- ferrous is 67 %. This implies that a total of 14.8 ktonne clean aluminium is recovered from the bottom ash in 2012.

From this point, two recovery factors can be calculated depending on the system boundaries. The first recovery factor is applied for the sub-system dealt with in this chapter, the bottom ash treatment plants. The metal losses due to oxidation are inherent to the system and cannot be controlled; therefore an additional recovery factor can be determined. The first recovery factor indicates the amount of aluminium, which can still be recovered. The second is applied at the system dealt with until now, and includes the metal losses due to oxidation, to give an overall indication of the recovery of aluminium. Based on the analysis performed, it can be concluded that 43 % of the potentially recoverable aluminium is recovered in 2012, while for the system dealt with until now 36 % is recovered. This implies that almost 20 ktonne of aluminium could additionally been recovered from the bottom ash in 2012. It can also be concluded that there is still a large difference in recovery factors between the different bottom ash treatment plants(Annex III). A detailed overview of this analysis can be found in table 6, while the calculations can be found in Annex I.

Table 6: assessment of the recovered aluminium and recovery factors

Description:	Value:
Aluminium in incinerated waste (ktonne)	41.2
Potential recoverable aluminium from bottom ash (ktonne)	34.0
Impurity level non-ferrous metal mix	10 %[21]
Non-ferrous recovered including impurities (ktonne)	28.0
Clean non-ferrous recovered (ktonne)	25.2[22]
of which is stainless steel (ktonne)	3.0[22]
Aluminium content non-ferrous	60 %
Aluminium content clean non-ferrous	67 %
Aluminium recovered (ktonne)	16.8
Clean aluminium recovered (ktonne)	**14.8**
Recovery factor clean aluminium with respect to aluminium in bottom ash	43 %
Recovery factor clean aluminium with respect to aluminium in waste	**36 %**

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[21] Assumption

[22] Data derived from Dutch Waste Management Association (2013)

4.4. Bottom ash as secondary material and allocation of energy

Bottom ash is also used for civil engineering applications, where it replaces natural aggregate. Due to the leaching of heavy metals and salts into the ground(water) additional measures are required to protect the environment. In the green deal the government and the Dutch Waste Management Association agreed, among other things, to further clean the bottom ash so it has the same characteristic as natural aggregate (Rijksoverheid , 2012). The recovery of (non-)ferrous metals does not contribute to better leaching conditions itself (KEMA, 2011), since this is mainly determined by metal salt compounds (Oudenhoven, 2014). However, wet treatment seems to improve the quality of the bottom ash, although the criteria for free application of the bottom ash are not yet met (Kok, 2014). This technology is still considered as pilot scale (KEMA, 2011) and has according to (Hu, et al., 2010) higher capital and operational costs.

Since the removal of metals does not contribute to the improvement it can be concluded that all energy used in the recovery of metals can only be allocated to the removal of metals and therefore there is no justification for the allocation of energy to the treatment of bottom ash.

Besides the use of bottom ash for road filling and other civil engineering application it can also be used in cement and concrete where It also replaces natural aggregate. By using the bottom ash the impurities are being immobilised within the structure of the concrete or cement. In these applications it is often demanded that aluminium is removed to less than 1 wt.%, since it can cause hydrogen bubbles in the concrete (BRL 2507, CUR recommendation 116), which could lead to strength reduction during stiffing of the concrete. If the aluminium content would be higher (which is not the case in this analysis) it could potentially justify the allocation of energy to the treatment of bottom ash. However, the first certification for the application of bottom ash in concrete was in 2013 (Heros, 2013) therefore no allocation can be made and this application is not considered in this analysis

4.5. The best available technology

In order to determine which technology is the best available technology in the Netherlands, it is important to know how these systems are being applied in relation to the other systems. As is discussed in the previous paragraphs, some of the described technologies can act as stand-alone bottom ash treatment plants, while others can be more seen as an addition to regular technologies.

An overview of the complementary systems is shown in table 7

Table 7: overview of standalone and complementary technologies

	Standalone bottom ash treatment plant	Additional technology
Standard dry recovery	x	Wet treatment, ADR
Wet treatment	x	
ADR		

As is shown before, ADR cannot be used as a stand-alone technology, but is rather used as an addition to the standard dry recovery technology. The combinations of standard dry recovery and ADR, or wet treatment, with or without standard dry recovery, are the options for the best available technologies at this moment. Besides the recovery of valuable metals, which generates an income for the MSWIs, also the application and quality of the bottom ash also plays an important role. While the combination of ADR and normal dry recovery is already applied on a commercial scale, wet treatment is still on a pilot scale. The quality of the reaming bottom ash, after the separation of metals, is however improved with the wet treatment. However, this currently does not meet the criteria to freely apply it in civil engineering applications. Which implies that, in order to achieve the targets set in the green deal, additional steps must be applied in order to achieve the target set in the green deal. The economics of the total package of technologies and treatments will therefore have an important influence in the choice of technology. Considering the Dutch regulations for wastewater, the discharge of water might be a problem for sweet water regions for the wet separation. At the same time there seems to be a difference of focus between the technologies where wet treatment is more focused on the treatment of bottom ash, while the focus of ADR is to allow a maximal recovery of valuable metals.

Comparing these technologies overall it can be concluded that it is hard to come up with a single technology which exceeds all others, since it depends on several factors, such as the quality of the bottom ash and additional steps required to improve its quality and the economics, how successful it is. Looking only at the recoverability of aluminium, ADR has an advantage. At this moment, ADR is the only system being applied and installed on a commercial scale in several Dutch MSWIs, as an addition to the normal dry recovery. Considering these factors it can be concluded that at this moment ADR, in combination with standard dry recovery for the larger particles, has to be considered as the best available technology for the recovery of aluminium.

4.6. Transport

Bottom ash is, in most cases, stored twice, once before it is treated in the bottom ash treatment plant and the second time before it is used for a civil engineering application. In order to store the bottom ash it must be transported. This is mainly done with shovels, as is described by Royal Haskoning (2009). Since bottom ash would also be stored if the metals where not recovered an allocation must be made for the additional energy used. Therefore, the internal transport movements are described in this process. Half of the transport movements are assessed to be for the recovery of metals from bottom ash. The argumentation for this is derived from figure 14.

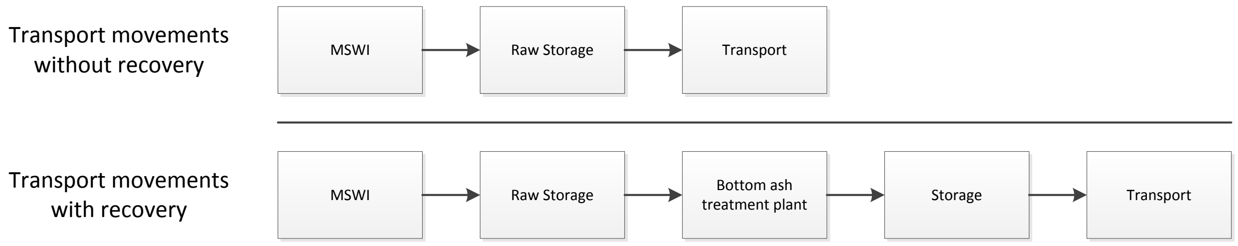

Figure 14: schematic overview of the transport movements with and without recovery of metals from MSWI bottom ash

As can been seen in the figure before, the amount of transport movements doubles with the usage of a bottom ash treatment plant. Therefore, half of the energy us for internal movement of the bottom ash is allocated to the recovery of ferrous and non-ferrous metals.

External transport is also required for some MSWIs, since the bottom ash is transported to a central bottom ash treatment plant. This central bottom ash treatment plant is located in Sluiskil (Heros). Bottom ash from several incinerators is shipped to this central plant, where valuable metals are recovered. Based on the amount of treated bottom ash from these incinerators, and an approximated distance to the central plant, an estimation is made of the distance to calculate the amount of tonne·kilometres. The details of this assessment can be found in table 8. Based on the tonne·kilometres for the bottom ash the energy requirements for the transport will be calculated.

Table 8: assessment of the tonne·km made to the central bottom ash treatment plant

MSWI	Bottom ash treated (tonne)[23]	Approximated distance (km)	tonne·km
AVR-AEC Rozenburg	315 018	150	47 252 700
REC Harlingen	45 332	300	13 599 600
SITA Roosendaal	76 077	100	7 607 700
Total	436 427		68 460 000

4.7. Energy used for aluminium recovery

The shipment of bottom ash to the central bottom ash plant could (partly) be compensated by a later shipment of bottom ash to its site of application, where it is used in civil engineering purposes. Therefore, an allocation for this shipment is also made in the discussion section as an extreme to indicate the impact. However, this allocation heavily depends on the projects that requires bottom ash. The energy input for internal transport and electricity used, is allocated based on the recovered metals. Based on the energy requirements per tonne metals recovered, the amount of energy required for aluminium is assessed.

The energy requirements for external transport of aluminium are based on the fuel use of the bottom ash transport, whit more than 68 million tonne·km, required to recover the valuable metals. The total fuel use can be calculated assuming a diesel usage of 0.022 l diesel per tonne·km (SKAO, 2011) for a barge with a capacity of 1 350 tonne (this includes the availably and detour factor). For the internal transport a diesel usage of 0.29 l/tonne is assumed (Royal Haskoning, 2009), of which half of the transports can be accounted to the recovery of ferrous and non-ferrous metals. This leads to the use of almost a quarter million litre of diesel, which can be allocated to the recovery of these metals. The electricity use of the bottom ash treatment plants was harder to establish. In absence of detailed literature values, a consultation of market parties was performed to determine the energy use of the bottom ash treatment plant. The details of this consultation can be found in Annex IV. In this analysis an energy use for the bottom ash treatment plant of 3.5 kWh/tonne is used. However, it must be stated

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[23] Data derived from Dutch Waste Management Association (2013)

that this could differ between the plants, depending on the design and age. This leads to a total electricity use of 5 934 MWh, of which 1 527 MWh is consider to be not generated in a MSWI. Since the recovered metals are not clean, an impurity factor of 10 % is applied to correct the recovered mass. Considering these values, a total of just over 7 TJ of diesel and 658 MWh of electricity are used for the recovery of aluminium from bottom ash. The details of this analysis are shown in table 9, while the full calculation can be found in Annex I.

Table 9: assessment of the energy requirements to recover aluminium from MSWI bottom ash

Description:	Value:
Bottom ash treated (ktonne)	1 696[24]
Bottom ash treated at central plant (ktonne)	436 [25]
External transport distance (tonne·km)	68 460 000
Diesel use barge 1350 tonne (l/tonne·km)	0.022[26]
Diesel use for internal transport(l/tonne)	0.29[27]
Diesel use internal transport (l)	247 449
Diesel use barge 1350 tonne (l)	1 521 333
Total diesel use (l)	1 768 783
Calorific value diesel (MJ/l)	36[28]
Total energy use for diesel (GJ)	**63 676**
Electricity use SOI (kWh/tonne)	3.5
Total Electricity used for SOI (MWh)	**5 934**
of which not generated by MSWI (MWh)	1 527
Non-ferrous metals recovered including impurities (ktonne)	28.0
Aluminium recovered (ktonne)	16.8
Impurities level ferrous	10 %
Ferrous metals recovered (ktonne)	123.3
Clean ferrous metals recovered (ktonne)	111[25]
Diesel use per tonne recovered material (GJ/ktonne)	420.8
Electricity use per tonne recover material (kWh/tonne)	58.9
Diesel use allocated to the recovery of aluminium (GJ)	**7 064**
Electricity use allocated to the recovery of aluminium (MWh)	**658**

It could be argued that the recovery of ferrous metals is necessary for a good recovery of the non-ferrous metals, which takes place at the start of the bottom ash treatment, and is less energy intensive than the process of recovering non- ferrous metals. In this analysis however, the energy required for ferrous and non-ferrous removal is divided over the metal output, in which all metals are expressed in tonne.

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[24] Data derived from DWMA (2013)

[25] Data derived from DWMA (2013) and Van Hoeve (2014)

[26] Data derived from SKAO (2011)

[27] Data derived from Royal Haskoning (2009)

[28] Data derived from Blok (2007)

4.8. Conclusion

In this chapter the recovery of non-ferrous metals from bottom ash with different technologies is described. Based on the characteristics of these technologies, an evaluation is made to determine the best available technology to recover aluminium. ADR, in combination with regular dry recovery, is considered to be the best available technology for this moment. From the analysis that is performed, it can be concluded that 14.8 ktonne clean aluminium is recovered from the bottom ash, which corresponds with a recovery factor of 36 %, based on the initial amount of aluminium present in the incinerated waste. This leaves, after deducting the losses, almost 20 ktonne of aluminium unrecovered. A large potential!

Besides the addition of ADR to the bottom ash treatment there also seems a difference between the recovery factors of the different MSWIs, which used regular bottom ash treatment, between 8-45 %. From the analysis it can be concluded that the amount of energy used for the recovery of metals in 2012 is 63 676 GJ of diesel fuel and 5 934 MWh of electricity. Allocating this to aluminium gives 7 064 GJ of diesel fuel and 658 MWh of electricity. An overview of this analysis, except for the allocation of energy is presented in figure 15.

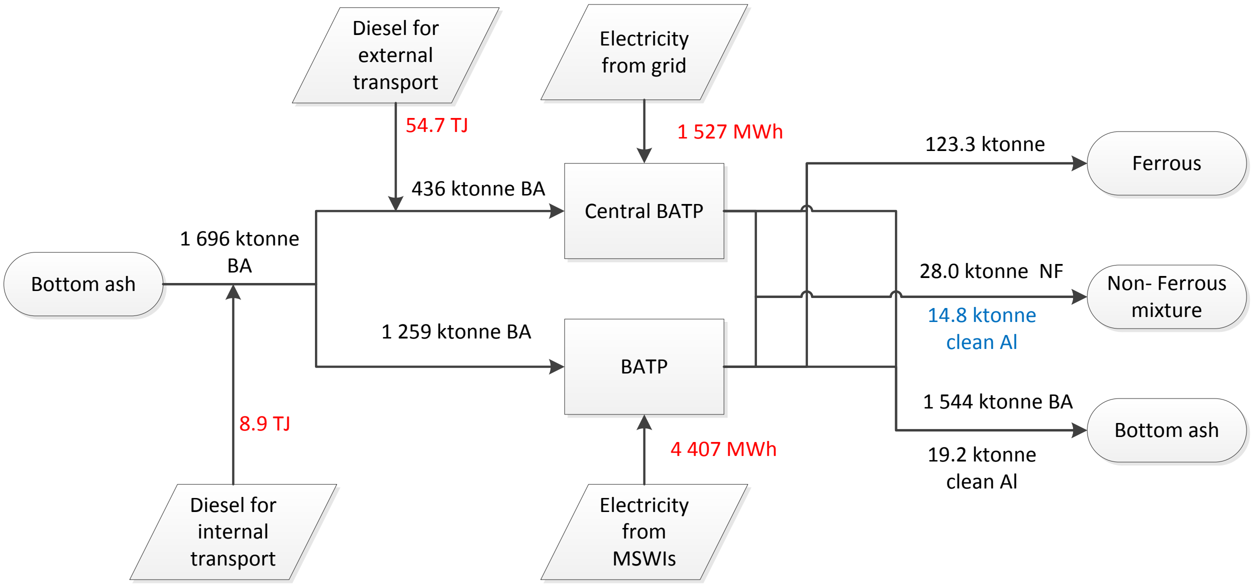

Figure 15: overview of the aluminium recovery from bottom ash and the energy use in this process

Chapter 5: Separating the non-ferrous metals

5.1. Introduction

The previous chapters dealt with the recovery of non-ferrous metals out of incinerator bottom ash. This chapter will proceed with the further separation of the non-ferrous metal mix into several metal fractions. This is done because the processors of these metals, such as aluminium smelters, require a certain quality grade in order to process the metals. There also is a financial incentive, since the separation of metals increases the total revenue. The separation of the non-ferrous mixture is done with several techniques, which make use of the different characteristics of the metals in order to separate them. In table 10 the composition of the non-ferrous mixture from one of the Dutch MSWIs is shown as is reported by Royal Haskoning (2009) in order to illustrate its composition. However, this composition does not necessary have to be the same between the different MSWIs and in time. In this table the density of these metals is also given, since this is in most cases the characteristic on which the separation is based.

Table 10: composition of non-ferrous scrap separated from bottom ash and density of components

	Composition[29]	Density (kg/m^3) @ 20 °C
Aluminium	62.7 %	2 700
Brass	6.8 %	8 400-8 730
Copper	3.6 %	8 960
Zinc	2.8 %	7 100
Stainless steel	1.4 %	7 500-8 000
Others (valuable metals and impurities)	22.7 %	-

Furthermore, an analysis is made to assess the distribution of the non-ferrous mix between the different technologies and the related energy use of these technologies for the separation of aluminium out of the non-ferrous mixture. A schematic overview of the sub-system, which is addressed in this chapter, can be found in figure 16.

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[29] Data derived from Royal Haskoning (2009)

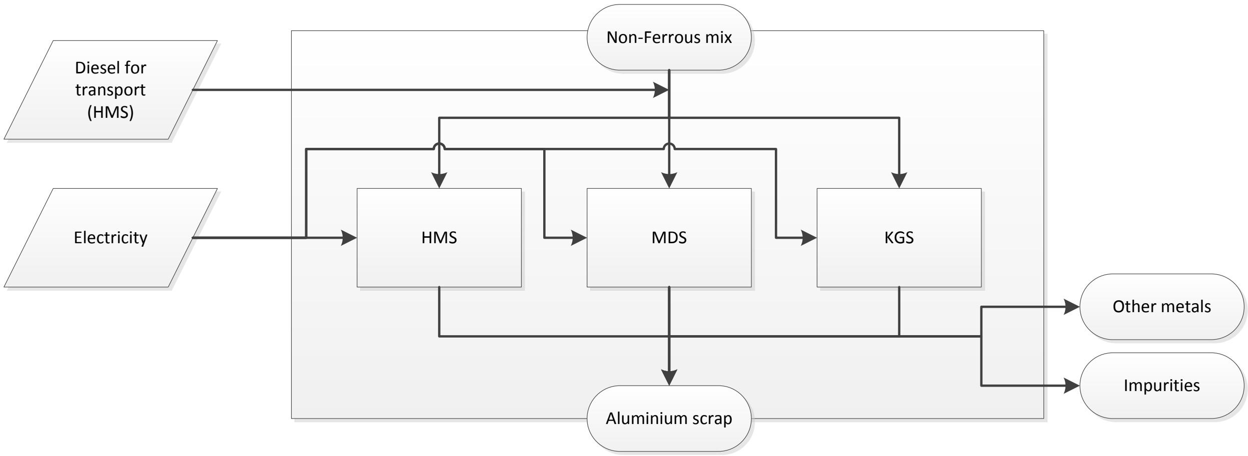

Figure 16: schematic overview of sub-system dealt with in chapter 5

5.2. Heavy Media Separation

Heavy Media Separation (HMS) is the technology most used to separate the metals based on difference in density. In table 10 it is shown that the difference in density between aluminium and other non-ferrous metals is quite large. The main application for HMS is separating the non-ferrous mixture from automotive shredder plants (Manouchehri, 2007). Besides these mixtures, they also use other non-ferrous mixes such as those from incinerator bottom ash. HMS uses heavy fluids consisting of ferrous-silicon suspensions. A typical HMS consists of two baths with different densities. In the first bath, a separation is made between magnesium (1 740 kg/m^3) and the other non-ferrous metals with a bath density of 2 000-2 400 kg/m^3. The other bath separates aluminium from the heavier metals with a density of the liquid of 3 000-3 300 kg/m^3. In this process stony materials, which are not fully removed in the bottom ash treatment plant, are also separated. In order to separate the different metals form the non-metallic fraction, the streams are led over an Eddy Current Separator. A schematic overview of a HMS bath is shown in figure 17.

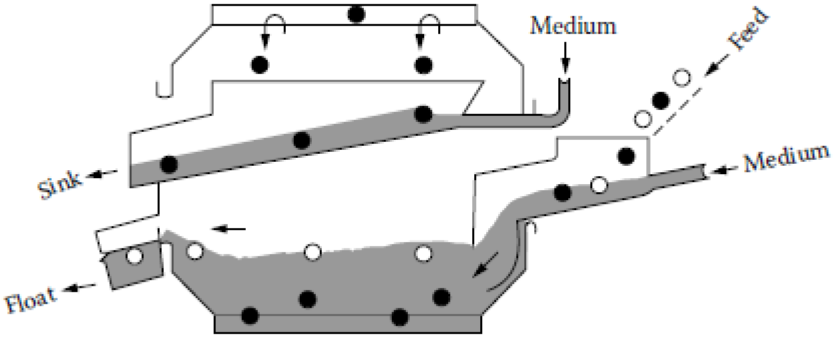

Figure 17: schematic overview of a drum type HMS bath[30]

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[30] Source: Schlesinger (2007)

The use of fluids also has downsides, such as:

- Impurities fed in with the non-ferrous mixture can influence the density of the liquid
- A wet process requires drying and washing of the metals and recovering of the media, which increases the costs
- Even with recovering systems media is lost, which increasing the operational costs as well

Due to these downsides, a dry system has been developed. The dry system uses a fluidized bed of sand, which can have an apparent density of 2 300 kg/m^3 and 4 600 kg/m^3. Since its limited to 2 300 kg/m^3 it is limited to the separation of heavy materials and cannot be used for the separation of lighter materials such as magnesium or plastics. This bed is kept fluidized with electric vibrators (Schlesinger, 2007). However, no data is available on the use of dry separation, which is used for the separation of non-ferrous mixtures from MSWIs, in contrast to wet separation. Therefore, it is assumed that this was not the case in this analysis.

5.3. Kinetic Gravity Separation

Kinetic Gravity Separation is a separation technology, which uses terminal velocity of particles to separate them. Therefore, this technology is potentially more useful for the separation of smaller particles, since smaller particles have a relatively low settling velocity. The principle on which the KGS is based is that if a particle is fed into a liquid stream, which has a horizontal direction, it will acquire the horizontal velocity of the fluid. Depending on the density, size and shape, these particles will acquire a vertical settling velocity. This effect allows the separation of different particles, as can be seen in figure 18. Applying this principle in a rotating fluid with different feeding points for different sized particles, allows the separation of different materials (Van Kooy, et al., 2004). This technology was applied in 2012 as part of the Central Upgrading Facility of Inashco for separating the non-ferrous fraction (2-12 mm) for Heros, which treats the bottom ash of several MSWIs without a bottom ash treatment plant and AVR Duiven (started the last quarter of 2012). At this moment, the share of non-ferrous metals treated with KGS is higher since the non-ferrous fraction of AEB and Attero Wijster are treated and a new Central Upgrading Facility is commissioned. In the near future the amount of non-ferrous metals treated by KGS will further increase since the fractions from Twence and Attero Moerdijk will also be treated (Inashco, 2014).

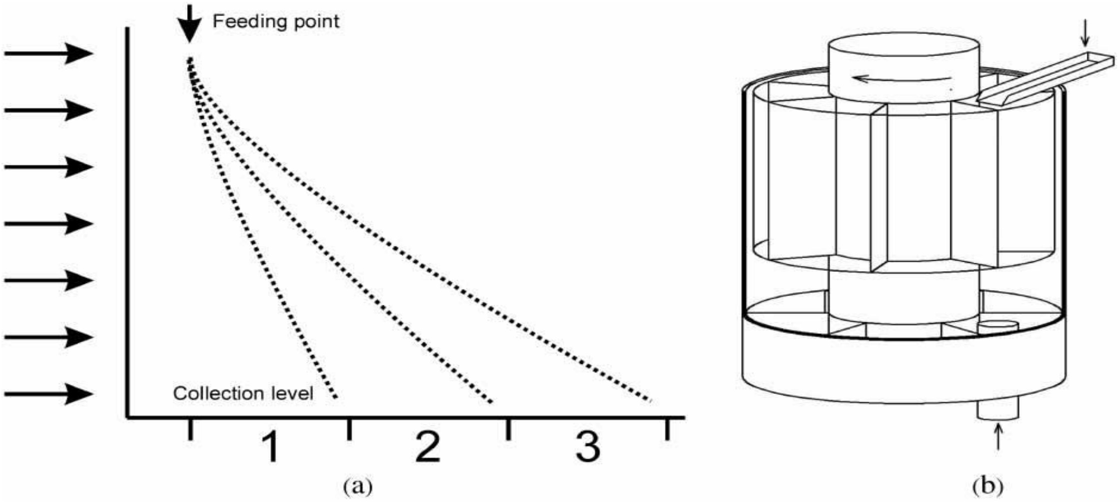

Figure 18: principle of kinetic gravity separation: (a) linear fluid flow; (b) rotational fluid flow[31]

5.4. Magnetic Density Separation

Magnetic Density Separation is a recent development (Liquisort, 2010) in separation of metals, although the principle behind it has been known for a while. A liquid with magnetic iron oxide particles with a size of 10-20 nm, is used in combination with magnets at the bottom of the tank. This liquid has a density similar to water under normal circumstances. However, if a gradient magnetic field is introduced at the magnets at the bottom of the separator, the density changes. The density then becomes the sum of the gravity plus the force of the magnetic field, which results in a density as function of the vertical distance from the magnet. A schematic overview of MDS is presented in figure 19. As can been seen a “stratified liquid” is formed under the influence of the magnet with different densities. Based on the apparent densities, a separation is made between several metals. However, according to Boni (2013) this technology could affect the recycling factor of small aluminium particles, since an oxidation reaction could occur with the solution. The advantage of this technology compared to HMS is that at the same time several metal streams can be separated. This technology had in 2012 not yet a market share in the separation of non-ferrous metals.

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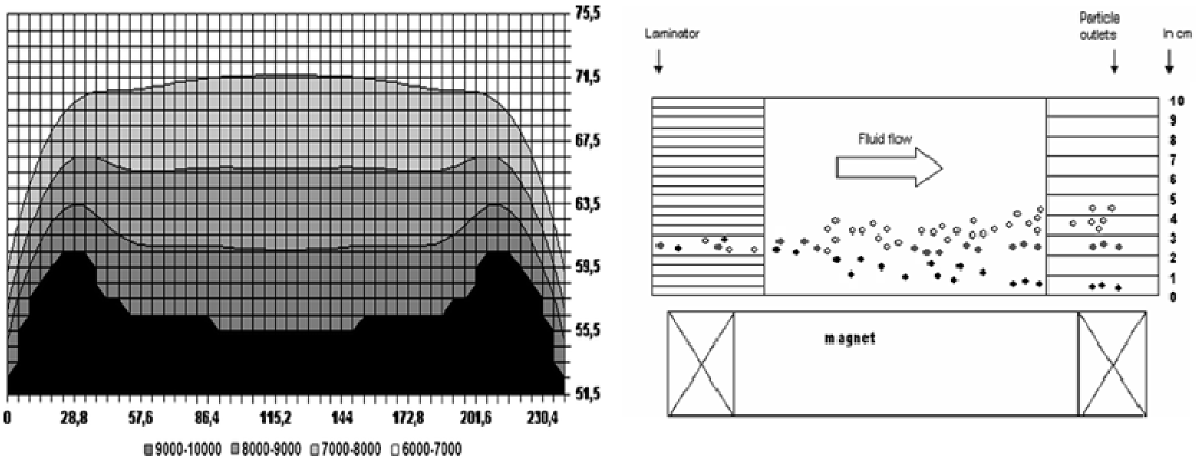
[31] Source: Van Kooy, et al. (2004)



Effective medium density in the magnetic liquid on top of the magnet (The magnet is at the **bottom** in this figure). The magnetization of the liquid is 7.817 A/m. The **x** and **y** values are in millimetres, the colours are showing the density in kg/m^3

Figure 19: principle of MDS[32] and schematic outline of a MDS[33]

5.5. Separating alloys

Hitherto in this chapter it has seemed as if the aluminium separation is only applied on a pure metal with one set of physical properties. However, as it is touched upon shortly in chapter 3, aluminium is mostly used in alloys; this has of course an impact on the separation. There are hundreds of alloys used of which some have a large application field and others are used for special purposes only (Schlesinger, 2007). The aluminium industry makes a distinction of two principal types of aluminium alloys, namely: cast and wrought alloys. Cast alloys have a higher degree of other materials in general, the so-called alloy agents or elements, than wrought alloys. For cast alloys the amount of alloying agent can go up to 20 % of alloying elements, while for wrought alloys this is only 10 %. Besides the total concentration of alloying elements, the main difference lays in the amount of silicon added. The main reason for adding silicon to cast alloys is to improve the castability, since the addition of more than 5 % silicon gives the alloys an almost isothermal solidification which decreases the effect of thermal expansion; it also contributes positively to the fluidity of the alloy, since silicon has a high heat of fusion (Apelian, 2009). In table 11 the general differences between cast and wrought alloys are shown. However, it must be stated that some specific alloys can differ from the general classification as has been made here.

Table 11: general differences between cast and wrought alloys[34]

	Cast alloys	Wrought alloys
Total alloying elements	up to 20 %	up to 10 %
Silicon concentration	> 5 %	< 1 %
Other major alloying elements	Mg and Cu	Mn, Mg, Cu and Zn

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[32] Source: Muchova, et al. (2009)

[33] Source: Bakker, et al. (2010)

[34] Data retrieved from UNEP-IRP (2011)

The differences in composition make it hard to use cast alloys scrap for the production of wrought alloys; however it is possible the other way around, since wrought alloys contain less other alloying elements. Therefore, it is preferable that alloys are separated based on their chemical composition in order to recycle them in their own sub-group, instead of “down cycling” them into alloys with a higher degree of alloying agents. At the same time it is possible to use these scrap types for the availability of alloying agents in times of high prices of silicon for instance. Adding primary aluminium to a batch of molten aluminium is also possible to dilute the impurities. In these cases the degree of down cycling is less.

There are several techniques to make a distinction between cast and wrought alloys; however to what extent these are applicable to aluminium alloys recovered from bottom ash is not known. Therefore, they are only briefly described in this paragraph. According to Schlesinger (2007), the following techniques can be used to distinguish between cast and wrought alloys:

- Cast alloys tend to have a lower initial melting temperature than wrought alloys and thereby lose some of its strength. If these particles are hot-crushed, the cast alloys are more likely to be crushed into smaller pieces than wrought alloys. However, this system never made it to a commercial scale
- Since there are small differences in appearance, handpicking is used in mostly low wage countries with reasonable efficiency
- The concentration of copper and silicon in cast alloys is higher and therefore can be sorted with X-ray, since these metals block more of the X-ray. With a different system the particles can be separated.
- With the application of different acids and bases the surface of aluminium is treated. Based on the chemical composition a discoloration takes place. With a different system the particles can be separated.

To the authors knowledge these techniques are not applied to the aluminium recovered from bottom ash and it is therefore most likely that most of the aluminium that is recovered, will be used for a casting alloy due to the mixture of different kinds of aluminium and the degree of other impurities.

5.6. Distribution of non-ferrous metals over the separation techniques

According to Rijkswaterstaat (2013), a total of 25.2 ktonne clean non-ferrous metal is recovered from bottom ash. From this the amount of stainless steel is deducted since stainless steel is almost entirely separated from the remaining NF at the bottom ash treatment plant. The clean amount of non- ferrous metals minus the stainless steel is, according to the DMWA (2013), 22.2 ktonne. In table 12 the estimated amount of the input is shown. This includes 10 % impurities such as organics and stone fractions, which gives an input of 24.7 ktonne. The distribution of the non-ferrous metal mix is considered to be as followed: since there was no market share considered for MDS in 2012, this technology has no input. HMS is considered the dominant technology and therefore it has the total input minus the share, which is treated with KGS. This amount is estimated on 2.7 ktonne based on the 2-12 mm fraction of the non-ferrous metals recovered by the MSWI, which ADR applied in 2012. This leaves 21.9 ktonne non-ferrous metals to be treated with HMS. The aluminium content of the clean non-ferrous metal mix is considered to be, similar to paragraph 4.3., at 67 %. Using the sorting efficiencies of HMS and KGS, which are respectively 96 % and 98 % according to Gaustad, et al. (2011) and Van Kooy, et al. (2004), the total aluminium output of the technologies is assessed to be 14.2 ktonne. The results are also shown in table 12, while the complete calculations can be found in Annex I.

Table 12: amount of non-ferrous metals en aluminium separated by several separation technologies

Description:	Value:
Total input separation techniques (ktonne)	24.7[35]
Total clean input separation techniques (ktonne)	22.2[36]
Input NF HMS (ktonne)	21.9
Input clean NF HMS (ktonne)	19.7[37]
of which aluminium (ktonne)	13.2
Input NF KGS (ktonne)	2.7
Input clean NF KGS (ktonne)	2.5[38]
of which aluminium (ktonne)	1.6
Input NF MDS (ktonne)	0.0
Input clean NF MDS (ktonne	0.0
of which aluminium (ktonne)	0.0
Efficiency HMS	96 %[39]
Efficiency KGS	98 %[40]
Efficiency MDS	NA
Output Al HMS (ktonne)	12.6
Output Al KGS(ktonne)	1.6
Output Al MDS (ktonne)	0.0
Total Aluminium output (ktonne)	**14.2**
Total recovery factor with respect to aluminium in waste	**35 %**

5.7. Energy use by the different separation technologies

In order to assess the amount of energy used to separate aluminium from the remaining materials, the energy use of the separation technologies has to be assessed. The energy use for HMS technology is 13.2 kWh/tonne, as reported by Royal Haskoning (2009). The energy use for the KGS is reported at 15 kWh/tonne (TU Delft, 2009) and is considered to be similar for incinerator metals. Inashco (2014) confirms the order of magnitude for this energy use. Given the in- and outputs for the technologies as calculated in paragraph 5.6., the energy uses allocated to the mass of aluminium is determined. The ratio between the clean aluminium recovered and the total non-ferrous input is 57.7 %, which corresponds with an energy use for the separation of aluminium of 191 MWh in 2012. Since additional transport is

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[35] Note: Clean non-ferrous minus stainless steel with a 10% impurity factor
[36] Data retrieved from DWMA (2013)
[37] Note: Total clean NF-KGS-MDS
[38] See Annex V for calculation
[39] Data retrieved from Gaustad, et al. (2011)
[40] Data retrieved from Van Kooy, et al. (2004)

required for the recovered non-ferrous metals in case of Heavy Medium Separation, this is added in the analysis. This is not the case for the Kinetic Gravity Separation, since this is done at the same site as where the bottom ash is treated. Based on the fuel use of a truck, which is, according to SKOA (2011) 0.04 l/tonne·km (including capacity and detour factor) and an average distance of 150 km, an energy use for fuel is allocated to aluminium of almost 2785 GJ for the transport to the HMS. The details of this analysis are shown in table 13, while the complete calculations can be found in Annex I.

Table 13: energy use for the separation of aluminium out of the non-ferrous mixture

Description:	Value:
Electricity use HMS (kWh/tonne)	13.2[41]
Electricity use KGS (kWh/tonne)	15[42]
Electricity use MDS (kWh/tonne)	5[43]
Input NF HMS (ktonne)	21.9
Input NF KGS (ktonne)	2.7
Input NF MDS (ktonne)	0.0
Electricity use HMS (MWh)	289
Electricity use KGS (MWh)	41.0
Total electricity use (MWh)	330
Diesel use truck >20 tonne HMS (l/tonne·km)	0.04[44]
Average distance HMS (km)	150
Average distance HMS (tonne·km)	3 288 649
Diesel use truck HMS (l)	133 982
Calorific value diesel (MJ/l)	36[45]
Energy use on diesel (GJ)	4 823
Total input (ktonne)	24.7
Total clean aluminium output (ktonne)	14.2
Total electricity use related to aluminium (MWh)	**191**
Total diesel use related to aluminium (GJ)	**2 785**

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[41] Data retrieved from Royal Haskoning (2009)
[42] Data retrieved from TU Delft (2009)
[43] Data retrieved from De Jong (2014)
[44] Data retrieved from SKOA (2011)
[45] Data retrieved from Blok (2007)

5.8. Conclusion

A total of 24.7 ktonne non-ferrous mixture is treated by the separation technologies. In order to assess the energy requirements, a separation of these technologies is made. Based on size distribution and the activities of companies in 2012, it is estimated that 21.9 ktonne is separated by Heavy Medium Separation and 2.7 ktonne by Kinetic Gravity Separation. This resulted in a total aluminium output of 14.2 ktonne, which is transported to the aluminium refiner. This implies that the recovery factor so far is 35 %. The energy requirements of these activities related to aluminium are assessed on 191 MWh of electricity and almost 2 785 GJ for diesel use. An overview of the sub –system analysed in this chapter is provided in figure 20.

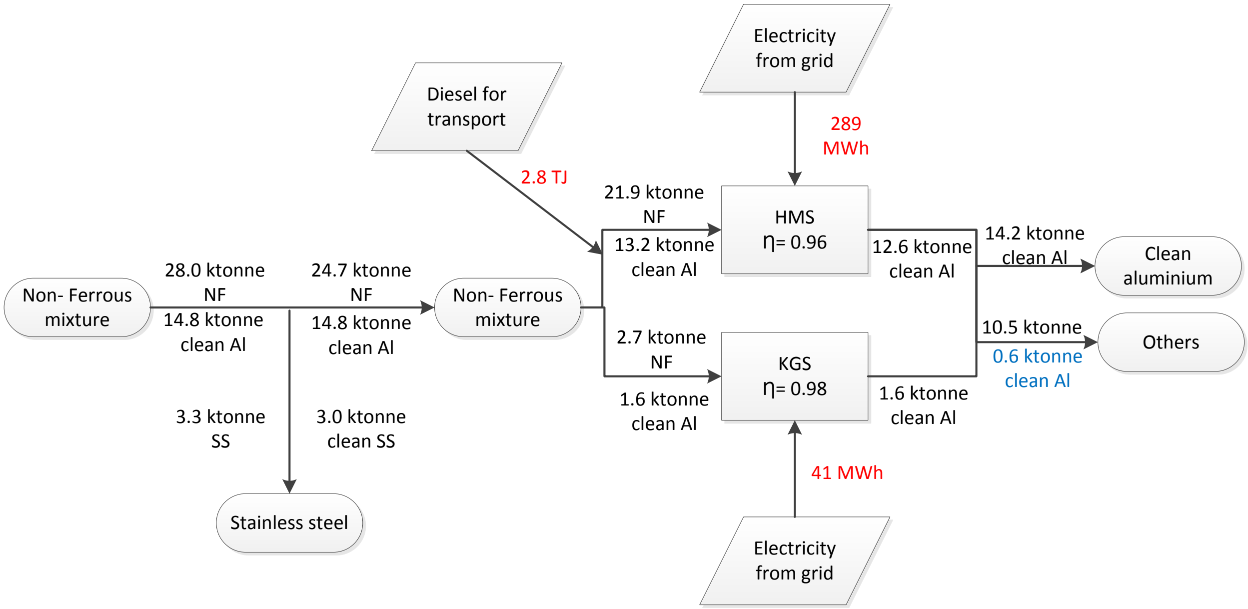

Figure 20: overview of separation of aluminium from the non-ferrous mixture

Chapter 6: Aluminium melting

6.1. Introduction

This chapter describes the final stage in the recycling of aluminium from incinerator scrap, namely the melting and casting. It also includes the recovery of aluminium from salt slag, which is used as a cover to protect the aluminium from further oxidation during the melting process. The Rotary Drum Furnace, which is used for melting aluminium scrap, such as aluminium from incinerator scrap, is described and the melting losses and energy requirements for this sub-system are assessed. Figure 21 gives an overview of the sub-system dealt with in this chapter.

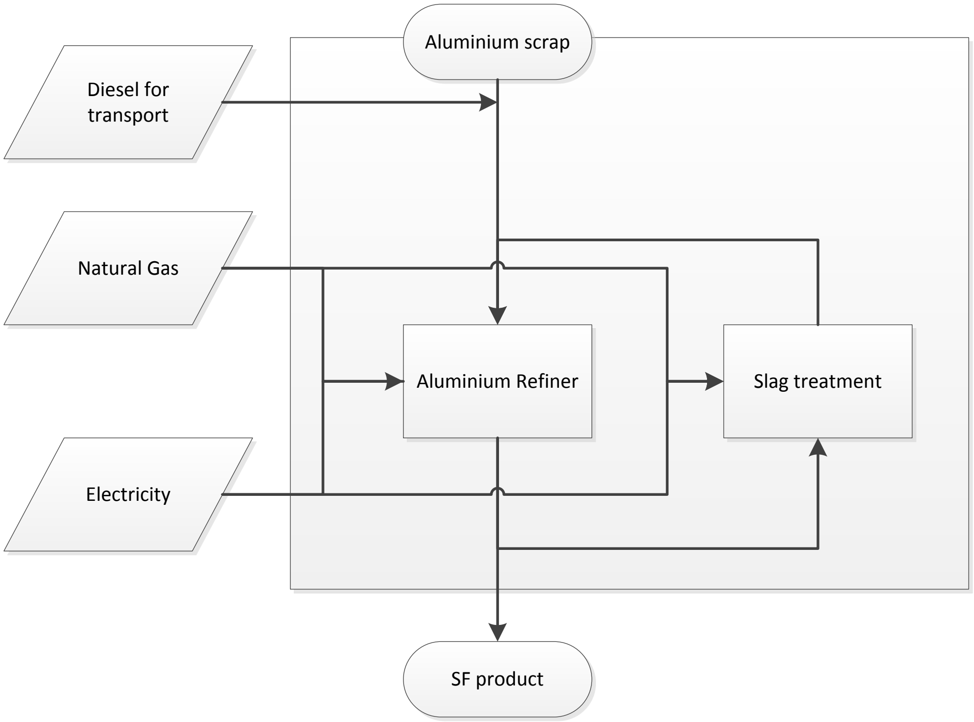

Figure 21: schematic overview of the sub-system dealt with in chapter 6

6.2. Aluminium melting

The separated aluminium is sold on the international market to recycling companies. Two types of recyclers recycle secondary aluminium, namely remelters and refiners. The type depends on the quality of aluminium. While remelters almost only deal with carefully selected wrought scrap and primary aluminium to dilute the impurities, refiners recycle the remaining scrap (Schlesinger, 2007). Considering the fact that remelters deal with carefully selected scrap, it is assumed that only refiners use incinerator scrap as feedstock.

According to the European Aluminium Association (2013), most refiners convert recycled material into foundry ingots. These ingots are used to produce aluminium castings in a later stadium. Refiners use several types of furnaces, depending on the quality of the scrap amongst others. For high-grade aluminium a reverberatory furnace is often used, while a rotary drum furnace is often applied for more contaminated an oxidized scrap. The size of the aluminium particles also influences the use of the furnace type. A rotary drum furnace handles the smaller particles mostly for example, while a reverberatory furnace is often used for larger particles (Schmitz, 2006). A sloping hearth furnace is used to melt mixed aluminium, which still contains some steel (Muchová & Eder, 2010). In most cases the heat required to melt the aluminium, is provided by a natural gas fired burner. A high surface area is required due to the high thermal conductivity and heat reflection of aluminium. Shallow baths are used to enlarge the surface area. The temperature of the metal in the furnace used for melting the aluminium, is typically in between 700 to 750°C (Schlesinger, 2007). In some cases the use of oxy fuel (pure oxygen instead of air) is applied to acquire a higher temperature, while in others a combination of oxy fuel and normal air is applied. The benefit of using oxy fuel is that fuel savings can be achieved since the temperature of the flame can be increased which shortens the residence time and therefore a higher production rate can be achieved. Also the generation of NO_x is eliminated in case of oxy fuel use due to the absence of nitrogen. This due to the fact that no nitrogen is introduced into the furnace, which allows a higher adiabatic flame temperature (Schmitz, 2006). If oxygen enriched air is used it depends on the total effect of higher temperature and lower partial pressure of nitrogen what the effect regarding NO_x will be. In order to achieve an even metal temperature the mix is often “stirred” (Schlesinger, 2007). Due to the previous described oxidation the aluminium contains already an oxidation skin (Al_2O_3) this is further enhanced by the high temperature in the furnace and the large surface area has also a negative influence on the oxidation rate. The further forming of oxides must therefore be limited. During the melting of the aluminium the aluminium oxide floats to the top of the bath and forms a second phase the so called “dross”. In order to separate the aluminium oxide from the molten aluminium and to reduce further metal losses a drossing flux is used in especially a rotary drum furnace. The flux consists of NaCl and KCl and some minor amount of fluoride salts (Schlesinger, 2007). This agent floats on top of the molten aluminium and thereby it reduces oxidation losses at the surface of the bath. Furthermore it has other advantages such as:

- The attachment of impurities and the dissolving of aluminium oxide to the flux, thereby allowing a quality improvement of the aluminium
- It promotes the coalescence of the aluminium droplets which would otherwise be captured in the oxide layer (this is mainly caused by the fluoride salts)

The contaminated flux or salt slag is further processed in order to recover as much as possible aluminium. Which will be described in more detail in the next paragraph.

Rotary Drum Furnace

The Rotary Drum Furnace (RDF) is designed to handle aluminium scrap with a higher oxidation grade and small individual particles and therefore it is ideal for handling incinerator scrap. The RDF has two variants, namely a tiltable and an non tiltable variant. Depending on the variant the construction may differ. But in general it consist of a long sloping tube with on one side a burner aligned. The scrap can be charged on the burner side and some models allow discharge on the other side. Also different burners can be mounted on one furnace. Due do the rotation of the furnace the material is moved which allows more exposure to the heat generated by the burner. The exposure to the heat is prolonged in tiltable and some non- tillable furnaces, since the flue gasses are forced into counter flow to the burner, which extends the residence time of these gases in the furnace. Due to the low quality scrap, which is normally used in a RDF, it is required to use drossing flux to protect the melt and collect the impurities. A RDF is able to de-coat aluminium to some degree before the melting process starts. This is done by increasing the temperature below a temperature of 350 °C since oxidation increases rapidly above this temperature (Schmitz, 2006). With an excess of air in order to allow the organic material to burn off. This exec of air will gradually be decreased depending on the oxygen level, which is a measurement for the organic contamination, in the flue gasses to minimize the oxidation of the metal. The temperature is than increased to start the melting phase in which the flue gas have a temperature of 1000°C. As the temperature of the metal increases less energy is required and the burner will reduce the fuel input. The aluminium will be overheated by 100°C in order to allow transport of the molten aluminium after tapping. This tapping is either done by removing the plug from a standard RDF in which case the molten aluminium is poured followed by the slag. In case of a tillable RDF the RDF is tilted a little bit over a horizontal position and the molten aluminium is poured out. By tilting the RDF somewhat more the slag is removed (Schmitz, 2006). A schematic view of a RDF is shown in figure 22.

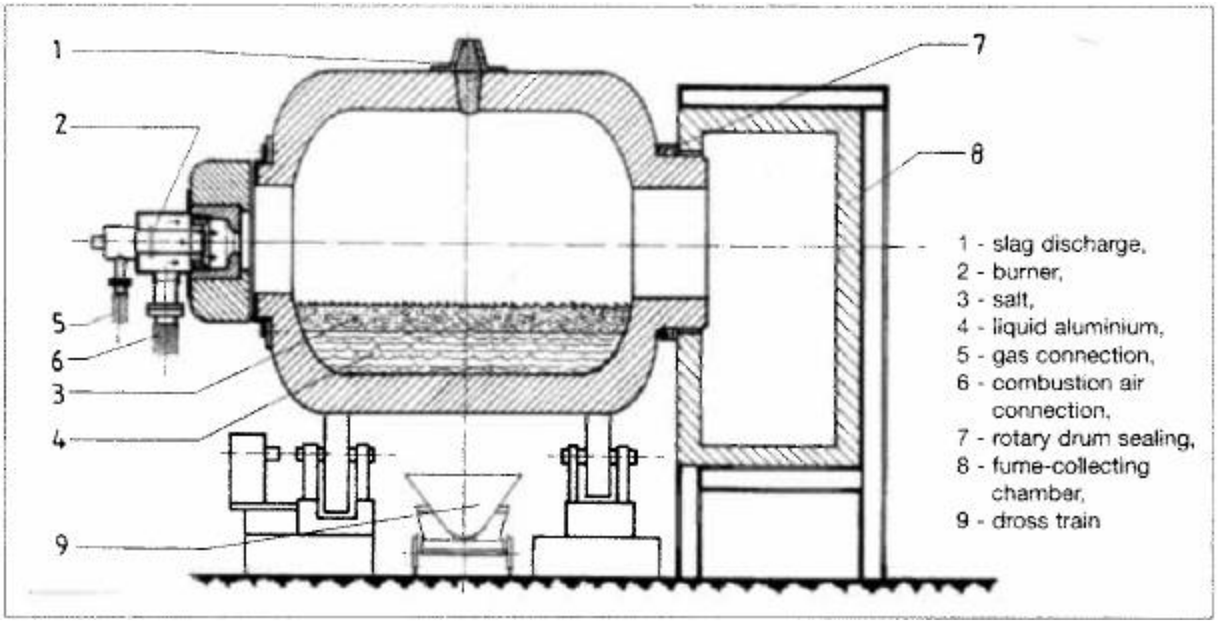

Figure 22: schematic overview of a rotary drum furnace[46]

The melted aluminium is directly send to a casting plant where direct ingots or other semi-finished products are casted or in some cases transported in liquid form to the customer where it is casted. These products can vary from deoxidation ingots, wildly applied generic alloys or specific custom made alloys (The Aluminum Association, 2008). The casting itself is not energy intensive (Green, 2007). However, there are substantial energy losses due to the cooling of the freshly poured ingot, which is cooled with water in order to solidify.

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[46] Source: Schmitz (2006)

Slag treatment

The removed slag contains according to the EAA (2013) between 5 and 20 % of metallic aluminium. In order to recover this, a slag processing plant is used. The amount of slag generated can according to Schmitz (2006) lay between 100 and 200 kg per tonne aluminium. The treatment of the slag consists of mechanical crushing after which a screening takes place to recover larger aluminium particles or metal granulate. The smaller particles are fed into a ball mill where particles larger than 1 mm are recovered. The recovered metal granulate which has an aluminium content of 80 % is fed back into the furnace. According to the EAA (2013) 75 % of the metal is recycled from the slag The remaining material consist mainly of salts and aluminium oxides, by mixing this with hot water the salt will dissolve after witch the aluminium oxides and other insoluble compounds can be filtered from the brine. The filtered material can be used to replace bauxite but is mostly used in the refractory industry (European Aluminium Association, 2013) (Schmitz, 2006). The salt in the brine is crystalized by evaporating the water after which it is further dried. To compensate for the losses, which occur during the melting, of the drossing flux, potassium chloride and some CaF_2 after which it can be reused as flux (Schmitz, 2006). The system in which aluminium is recovered from slag is shown in figure 23.

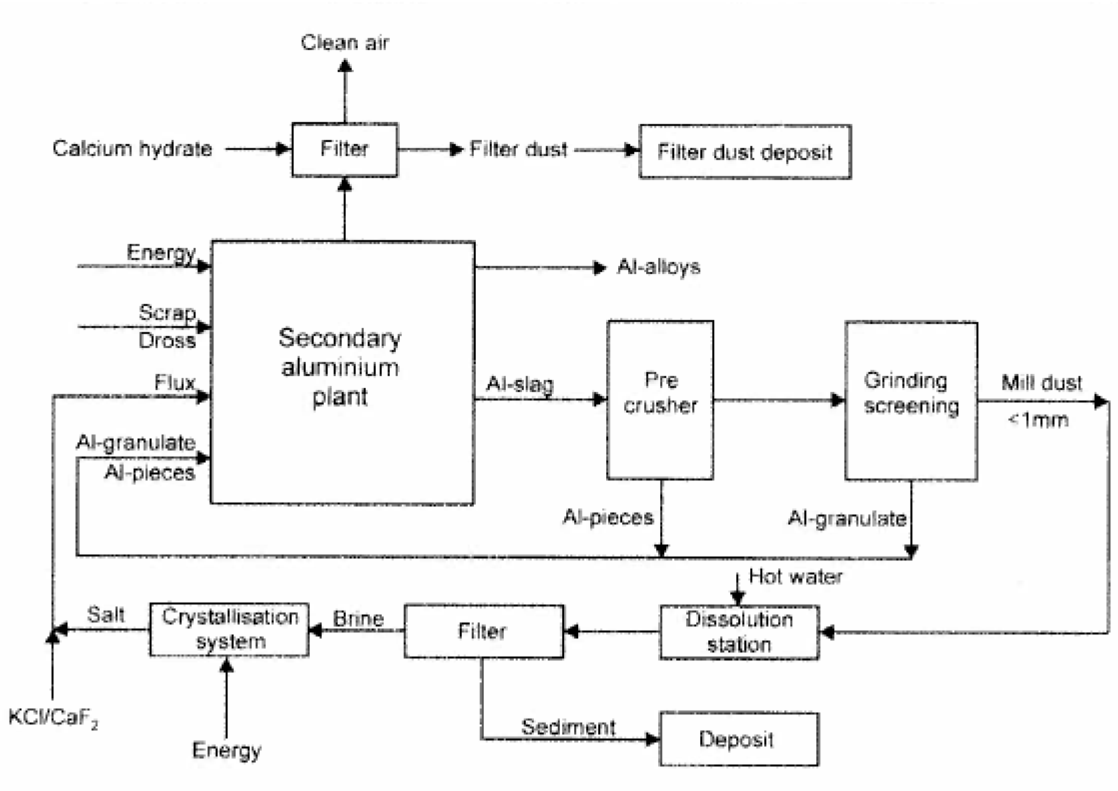

Figure 23: schematic overview of slag treatment as part of the secondary aluminium plant[47]

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[47] Source: Schmitz (2006)

Alloy applications of incinerator scrap

In order to obtain the desired alloy composition the input must be considered carefully. This consideration is based on the cheapest option to obtain the alloy with the available materials. These materials can consist of different alloys and sometimes it can be necessary to add primary aluminium as well. Looking at specific at incinerator scrap, which is primary used in the production of DIN 226 alloys (Willbold, 2014) (De Jong, 2014). The composition range of the DIN 226 alloys is given in table 14.

Table 14: chemical composition of DIN 226 alloys[48]

Chemical composition (%)	
SI	8.0-11.0
Fe	≤1.3
Cu	2.0-4.0
Mn	≤0.55
Mg	0.05-0.55
Cr	≤0.15
Ni	≤0.55
Zn	≤1.2
Pb	≤0.35
Sn	≤0.25
Ti	≤0.25
Other components	Single 0.05 total 0.25

In these alloys 20 to 30 % of incinerator scrap is used in combination with other scrap such as skimmings and turnings of the DIN 226 alloy and other aluminium scrap (Willbold, 2014).

Another application for which incinerator scrap is used is in deoxidation ingots (or other forms such as cubes or semi spheres) for the deoxidation of steel in the basic oxygen furnace (European Commission, 2013). This requires a high aluminium concentration. The specification range in which this is applied is shown in table 15. However, due to the current market conditions the use of aluminium in DIN 226 is more favourable (De Jong, 2014).

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[48] Data retrieved from Matweb (2014)

Table 15: specification range deoxidation aluminium based on JIS an ASTM standards[49]

Chemical composition (%)	
Cu	0.1-5
Fe	0-3
Mg	0.1-2.5
Mn	0-1
Si	0-1
Ti	0
Zn	0.1-5.5
Al	85-99

Melting losses

An important parameter for refiners in the purchase of scrap aluminium is the melting loss of a batch aluminium. The melt loss is a combination of several losses. These losses consist of oxidation losses in the furnace, the losses of some alloy metals such as magnesium which is burned off, the escape of small aluminium particles with the flue gas and dust and the to the losses to the slag. The melting losses vary depending on the source of the scrap. Table 16 gives an overview of typical recoveries according to ASM international, a typical value for incinerator scrap is not mentioned by them.

Table 16: typical recoveries of aluminium scrap[50]

Scrap type	Metal Recovery (%)
Building scrap	99
Transport scrap	96.1
Foil scrap	96.1
Used beverage cans	98.5
Engineering scrap	95.8
Scrap from consumer durables	95.4
Total old scrap	96.6
Total scrap	98.1

Looking specific at the losses in incinerator scrap total melting losses are known of 40 % with an average of 15 to 20 % (De Jong, 2014). This however includes the losses earlier in the process. The melting losses in the RDF are assessed on 5 % (Schlesinger, 2007) (Schmitz, 2006). Since the aluminium used for De(s)ox and DIN 226 alloys is melted in a RDF no distinction is made in melting losses or energy requirements. This implies that a total of 13.5 ktonne of recovered aluminium can be applied as a semi-finished product. This includes the losses in the internal recycling of the aluminium slag. With the reintroduction of 13.5 ktonne of aluminium in the market a recycling factor of 33 % is achieved. The details of this analysis are shown in table 17, while the complete calculations can be found in Annex I.

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[49] Data retrieved from ASM International (2001)

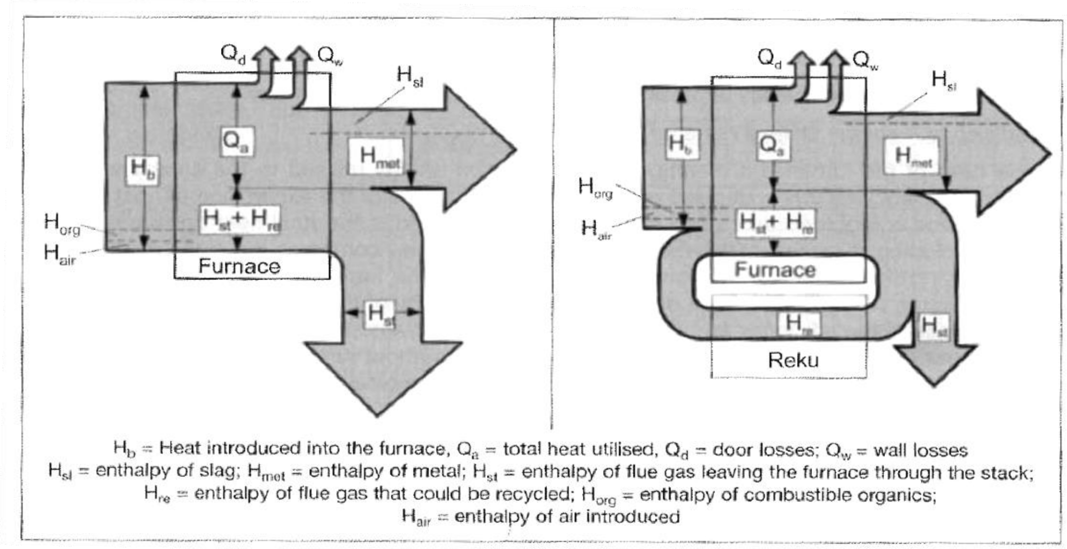
[50] Source: Boin & Bertram (2005)

Table 17: calculation of the melting losses and recycling factor

Description:	Value:
Aluminium to refiner (ktonne)	14.2
Total melting losses in RDF	5.0 %[51]
Aluminium in semi-final product(ktonne)	**13.5**
Total recycling factor with respect to aluminium in waste	**33 %**

Energy use in the production of aluminium semi-finished products

The theoretical energy use for heating and melting pure aluminium is 316 kWh/tonne when (over)heated to 720°C. Due to impurities and alloys the energy requirements are most likely somewhat lower since the distance between the atoms increases in the crystal lattice in case of alloy agents (which decreases most likely the melting point). In practice the efficiency of the RDFs are lower. According to Schmitz (2006) the energy use of a Rotary Drum Furnace depends on the type of furnace and burner between 400 and 1 000 kWh/tonne (in this report 700 kWh/tonne is used) It is assumed that this is supplied by firing natural gas. This gives an efficiency between 32 % an 79 % for the RDF based on pure aluminium. The inefficiency is caused due to heat losses. The main loss of heat is due to the losses in the flue gas, which leaves the furnace a high temperature. Also the heat losses from the slag are considerable. The efficiency can be improved by applying a heat recuperation system but this is an economical consideration since these systems can be easily clocked by dust and other impurities, which adds to the maintenance costs. In figure 24 a Sankey diagram is shown of the energy losses in a furnace with and without recovery.



H_b = Heat introduced into the furnace, Q_a = total heat utilised, Q_d = door losses; Q_w = wall losses
H_{sl} = enthalpy of slag; H_{met} = enthalpy of metal; H_{st} = enthalpy of flue gas leaving the furnace through the stack;
H_{re} = enthalpy of flue gas that could be recycled; H_{org} = enthalpy of combustible organics;
H_{air} = enthalpy of air introduced

Figure 24: Sankey diagram of aluminium furnace losses with and without heat recovery[52]

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[51] Data retrieved from Schmitz (2006) & Schlesinger (2007)

The use of electricity is ratter limited in this process compared to the use of natural gas and is assess on 10 kWh/tonne (Schlesinger, 2007) (EAA, 2013).

Furthermore energy is used in the recycling an recovery of aluminium from slag which consumes 170 kWh/tonne aluminium produced on natural gas and 2.5 kWh/tonne aluminium produced on electricity (Schlesinger, 2007) (EAA, 2013). This leads to an overall energy use of more than 42 TJ on natural gas, an electricity use of 169 MWh. Since in the most cases the aluminium is transported to German refiners the transportation is also included in this analysis. An average distance of 500 km by truck is assumed which leads to a fuel use of 10.4 TJ. Detailed information is shown in table 18, while the complete calculations can be found in Annex I.

Table 18: calculation of the energy requirements for melting aluminium from incinerator scrap

Description:	Value:
Aluminium to refiner (ktonne)	14.2
Aluminium in semi-final product(ktonne)	13.5
Natural gas use melting (kWh/tonne)	700[53]
Electricity use melting (kWh/tonne)	10[54]
Natural gas use slag treatment (kWh/tonne aluminium)	170[54]
Electricity use slag treatment (kWh/tonne aluminium)	2.5[55]
Distance to refiner (km)	500
Distance to refiner (tonne·km)	7 118 167
Diesel use truck >20 tonne(l/tonne·km)	0.04[55]
Diesel use truck >20 tonne(l)	289 999
Calorific value diesel (MJ/l)	36[56]
Natural gas use melting and slag treatment (GJ)	**42 359**
Electricity use melting and slag treatment (MWh)	**169**
Energy use diesel (GJ)	**10 440**

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[52] Source: Schmitz (2006)
[53] Data retrieved from Schmitz (2006)
[54] Data retrieved from Schlesinger (2007) & EAA (2013)
[55] Data retrieved from SKOA (2011)
[56] Data retrieved from Blok (2007)

6.3. Conclusion

This chapter describes the melting and casting of aluminium from inclinator scrap. From the 14.2 ktonne of aluminium, which is fed in the furnaces, 13.5 ktonne ends up in the semi-finished products. This gives a recycling factor over the aluminium present in Municipal Solid Waste of 33 %. The energy requirements to transport, melt and cast this aluminium are more than 42 TJ on natural gas, 169 MWh on electricity use and 10.4 TJ diesel used for transportation. An overview of the aluminium melting is presented in figure 25.

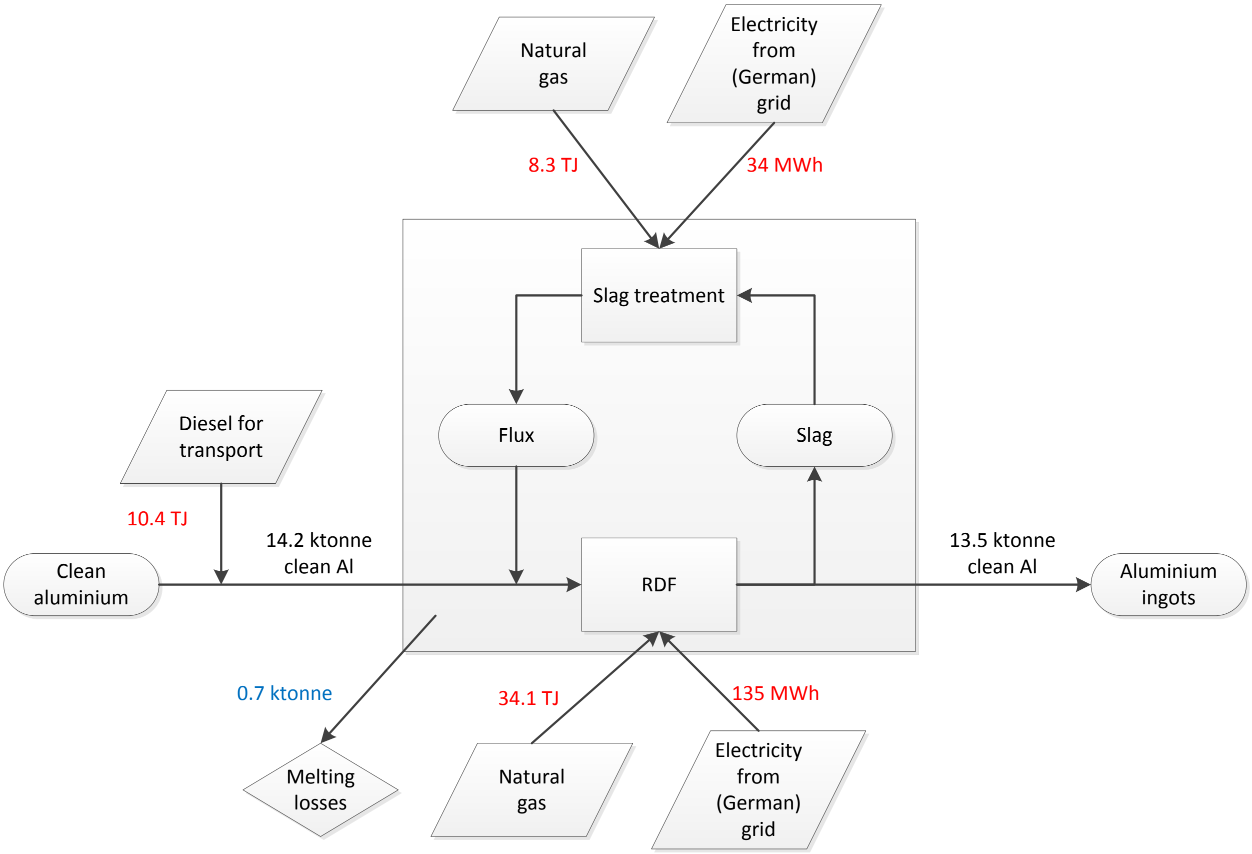

Figure 25: overviews of aluminium melting

Chapter 7: CO_2 emissions

7.1. Introduction

In this chapter, the CO_2 emissions from the recovery and refinery of aluminium from bottom ash are assessed. This is based on the processes and their energy usage as is described in the previous chapters. In order to compare the CO_2 emission with primary aluminium and regular aluminium scrap, these processes are briefly described, and their CO_2 emissions are presented.

7.2. Primary aluminium

Primary aluminium uses bauxite as raw material. Bauxite contains one or more aluminium hydroxide compounds and other materials, such as silica and iron oxides (EAA, 2013). Bauxite is milled and crushed, after which it is treated under elevated temperature and pressure with sodium hydroxide and lime in the Bayer process, where the aluminium hydroxides dissolves in the basic solution and the remains are filtrated, which gives the characteristic red mud. By decreasing the temperature of the solution the aluminium hydroxide precipitates. This is followed by calcination of the aluminium hydroxide after which alumina is formed. According to the EAA (2013) 2.3 tonne bauxite is required in Europe to produce 1 tonne of alumina.

With the Hall-Héroult process the alumina is converted into aluminium. The aluminium smelters use electrolyse to reduce the alumina, which is performed at 950°C in a fluorinated bath (mostly cryolite). The alumina reacts with the carbon anode at the top of the smelter into aluminium and CO_2. The molten aluminium is tapped from the pots and further alloyed to the costumers' specifications, by adding alloy agents but clean secondary aluminium can also be used. The aluminium is casted into several semi-finished products (EAA, 2013).

This electrolyse is the most energy intensive part of the primary aluminium production. According to the EAA (2013), the energy consumption of the in Europe melted aluminium was 14 887 kWh/tonne aluminium in 2010, while for the imported aluminium (44 %) an average of 15 500 kWh/tonne is used.

Looking at the CO_2 emissions in this process, due to the high electricity use, the emission factor of electricity has a large influence. The EAA (2013) calculated a CO_2 emission of 7 788 kg/tonne for imported aluminium and 7 703 kg/tonne for the aluminium produced in Europe for the total production chain of aluminium in 2010. Unfortunately there is no more recent data available.

Table 19: CO_2 emissions primary aluminium

	CO_2 emissions (kg CO_2/tonne ingot)[57]
Primary aluminium imported in Europe	7 788
Primary aluminium production in Europe	7 703

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[57] Data retrieved from EAA (2013)

7.3. Secondary aluminium

Secondary aluminium consists of two types of aluminium scrap: new and old scrap. New scrap originates from aluminium losses during several production processes, mainly of wrought aluminium, and can directly be re-melted. Old scrap is recover aluminium from various products at the end of their lifetime. These sources are, amongst others: transport, construction, packaging, electrical and mechanical engineering and household appliances. Most of these categories have a lifetime of more than 10 years except packaging, which has an average lifetime of less than a year (Schmitz, 2006). Depending on the type of application of the aluminium, there are also different efficiencies for the collection of aluminium. While aluminium used in building materials has a collection efficiency of 92 %-98 %, used beverage cans only have an efficiency of 48 % (Boin & Bertram, 2005). In table 20 an overview of the sectors in which aluminium is applied and the effect on the recycling is given.

Table 20: overview of recycling parameters of aluminium[58]

Product range	Average Product Life (years)	Estimated Recycle Rate (%)	Estimated Metal Recovery (%)
Building and construction	40	15	85
Transportation: aerospace	30	30	90
Transportation: auto and light truck	13	80	90
Transportation: trucks, buses and trailers	20	70	90
Transportation: rail	30	70	90
Transportation: other	20	70	90
Consumer durables	15	20	90
Electrical	35	10	90
Machinery and equipment	25	15	90
Containers and packaging: foil	1	2	80
Containers and packaging: others	1	25-60	90
Other	15	20	90

Due to variety of the aluminium applications, with each have their own alloy composition, a careful separation has to be made between these alloys and other impurities. This is done preferably by mechanical separation with, similar technologies as for the separation of aluminium from the non-ferrous mixture earlier described in this report. Painted materials, such as used beverage cans, are often sent to a de-coating plant where for example pyrolysis is applied at approximately 400°C, to reduce the organic content. The aluminium scrap is then, depending on its chemical composition, sent to an aluminium smelter for wrought alloy production or a refiner for cast alloy production.

The CO_2 emissions are, due to lower energy consumption for the production of secondary aluminium, considerable lower. According to the EAA (2013) the CO_2 emission of new scrap is, on average,

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[58] Source: Schleslinger (2007)

349 kg/tonne aluminium and for old scrap this is 482 kg/tonne in 2010. This difference is caused by the additional metal losses and extra treatment requirements for the old scrap.

Table 21: CO_2 emissions secondary aluminium

	CO_2 emissions (kg CO_2/tonne ingot)[59]
New scrap recycling	349
Old scrap recycling	482

7.4. CO_2 emission in the supply chain of aluminium from bottom ash

The emission of CO_2 in the supply chain is caused by the use of electricity, diesel or natural gas. In this paragraph the energy requirements from the several sub-systems are combined in order to give an overall CO_2 emission, as is custom for primary aluminium and regular scrap aluminium as well.

Natural gas.

Aluminium refiners only apply natural gas as described in chapter 6. Based on the assessment made in chapter 6, the total energy requirement for natural gas was more than 42 TJ. According to Agentschap NL (2013), the CO_2 emission of dry natural gas is 56.6 kg/GJ in the years 2010-2012. Assuming that the emission factor is similar for the aluminium refiners in Germany, and that the recovered amount of aluminium is processed in the same year, it gives us a total emission of 2.39 ktonne of CO_2 for the use of natural gas. The details of this analyse are given in table 22.

Table 22: CO_2 emissions from natural gas in the supply chain

Description:	Value:
Natural gas use (GJ)	42 359
CO_2 emission natural gas (dry) (kg/GJ)	56.5[60]
CO_2 emission natural gas (ktonne)	**2.39**

Diesel

Diesel is used in all transport movements from one sub-system to another and within some sub-systems as well. A total of 20 TJ is used on diesel for transportation. Based on the CO_2 emission factor for diesel of 74.3 kg/GJ, as is stated by Agentschap NL (2013), the total emission is assessed on 1.51 ktonne CO_2. The details of this analyse are given in table 23.

Table 23: CO_2 emissions from diesel in the supply chain

Description:	Value:
Diesel (GJ)	20 289
CO_2 emission diesel (kg/GJ)	74.3[61]
CO_2 emission diesel (ktonne)	**1.51**

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[59] Data retrieved from EAA (2013)

[60] Data retrieved from Agentschap NL (2013)

Electricity

Electricity is not only used in the total supply chain, similar to diesel, but it is also generated by the MSWIs of which a part is used by the bottom ash treatment plants. The primary task of an MSWI is the incineration of waste whereby a part of the generated energy is usefully applied in the form of electricity and heat. The quantity of the electricity produced by the MSWIs replaces electricity that otherwise would be produced by the Dutch electricity generation system, therefore lessening the CO_2 emissions.

The bottom ash treatment plants use 489 MWh of electricity originating from MSWIs. With a CO_2 emission factor for the Dutch electricity grid of 0.44 kg/kWh in 2011, according to CBS (2013), which is assumed to be similar in 2012, this leads to a CO_2 saving of 215 tonne. With this amount of electricity, only the direct energy use of the bottom ash treatment plant is assumed. The electricity for the remaining operations of the MSWIs, such as the flue gas treatment, is left out of the scope, since this would also have to occur without the metal recovery.

The aluminium refiners are assumed to be in Germany as discussed in chapter 6, so the German emission factor is applied for the electricity use of these refiners. The German emission factor is provisionally estimated on 0.576 kg/kWh for 2012, according to Umweltbundesamt (2013). With an electricity use of 169 MWh for the refiners, this leads to an emission of almost 97.4 tonne of CO_2 for the refining of the aluminium recovered from bottom ash. The remaining electricity, 360 MWh, is produced and used in the Netherlands. With an emission factor for 0.44 kg/kWh in 2011, according to CBS (2013), and assuming this is similar in 2012, the emission would be almost 158.5 tonne CO_2.

This leads to an overall CO_2 emission due to the use of electricity of 41 tonne in the total supply chain. The details of this analyse are given in table 24.

Table 24: CO_2 emissions from electricity in the supply chain

Description:	Value:
Total electricity use (MWh)	1 018
From which produced at MSWI (MWh)	489
From which used by refiners which are assumed in Germany (MWh)	169
Electricity used from the Dutch net (MWh)	360
CO_2 emission Dutch electricity mix 2011 (kg/kWh)	0.44
CO_2 emission German electricity mix 2012 (kg/kWh)	0.58
CO_2 emission savings electricity MSWIs (tonne)	215.1
CO_2 emission refiners (tonne)	97.4
CO_2 emission Dutch electricity (tonne)	158.5
Total CO_2 emission electricity (tonne)	**41**

CO_2 emissions due to recovery and recycling process

Based on the total emission of the different energy sources, the CO_2 intensity of the process is calculated. A total CO_2 emission of 3 942 tonne is emitted for the recovery and recycling of aluminium from bottom ash. With a total of 13.5 ktonne aluminium recycled, the CO_2 intensity is assessed on

291 kg/tonne. The complete details are shown in table 25, while the distribution of the emission over the various processes is shown in figure 26.

Table 25: CO_2 emissions and CO_2 intensity of the recovery and recycling process

Description:	Value:
CO_2 emission in recovery and recycling of aluminium (tonne)	**3 941**
Total aluminium recycled (ktonne)	13.5
CO_2 intensity (kg/tonne)	**291**

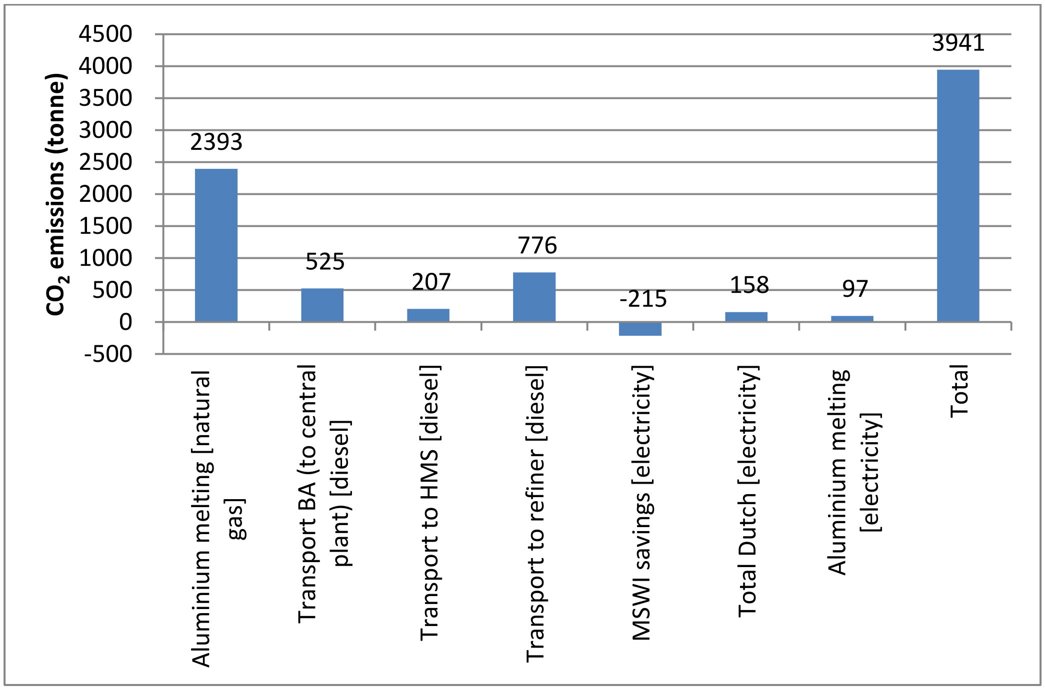

Figure 26: CO_2 emissions in the recovering and recycling of aluminium from bottom ash

CO_2 emission savings including the oxidation of aluminium

The oxidation of aluminium within the furnace of the MSWI contributes to the total amount of heat generated as is discussed in chapter 3. The oxidation of aluminium releases an amount of energy, which is not represented in the average calorific value of waste as calculated by Agentschap NL (2013), since this is the sum of calorific value of different waste categories times the amount of waste in those categories. The calorific value for non-ferrous metals is zero (Agentschap NL, 2010). Therefore, additional energy is released during combustion without the emission of CO_2, which effectively lowers the CO_2 emission factor for waste.

With a total of 7 471 ktonne MSW incinerated in 2012, a total amount of energy is generated of 71.72 PJ. According to Agentschap NL (2013), 54 % of the energy originates from the biogenic part, which implies that 32.99 PJ is generated by the non-biogenic part. Adding the amount of energy generated by the oxidation of aluminium (0.19 PJ), gives a total amount of energy generated, namely 33.19 PJ

Since the total CO_2 emission is not affected, a new emission factor is calculated including the oxidation of aluminium. The difference between the original emission factor and the new one is a measure for the CO_2 savings, namely 7 147 tonne CO_2. The details are presented in table 26.

Table 26: CO_2 emission savings due to oxidation of aluminium

Description:	Value:
MSW incinerated (ktonne)	7 471[61]
Calorific value (MJ/kg)	9.6[62]
Energy released due to incineration (PJ)	71.72
Biogenic part calorific value	54 %[34]
Energy generated by non-biogenic MSW (PJ)	32.99
Energy release due to aluminium oxidation (PJ)	0.19
Total energy generated non-biogenic + aluminium (PJ)	33.19
Emission factor (kg/GJ)	106.3[64]
Biogenic part emission factor	65 %[64]
Emission factor non-biogenic (kg/GJ)	37.21
CO_2 emission non-biogenic (tonne)	1 227 516
Emission factor non-biogenic + aluminium (kg/GJ)	36.99
Difference in emission factors (kg/GJ)	0.22
CO_2 savings due to aluminium oxidation (tonne)	**7 147**

The CO_2 savings from the oxidation are included into the system to calculate the total emission of the recovery and recycling of aluminium. Based on the total CO_2 emissions, which are -3 205 tonne, the CO_2 intensity is determined. For the process of recovering and recycling aluminium, including the oxidation of aluminium, the CO_2 intensity is -237 kg/tonne. The complete details are shown in table 27, while the distribution of the emissions over the various processes is shown in figure 27.

Table 27: CO_2 emissions and CO_2 intensity of the recovery and recycling process including CO_2 savings due to oxidation of aluminium

Description:	Value:
CO_2 emission in recovery and recycling of aluminium (tonne)	**-3 205**
Total aluminium recycled (ktonne)	13.5
CO_2 intensity (kg/tonne)	**-237**

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[61] Data retrieved from Rijkswaterstaat (2013)

[62] Data retrieved from Agentschap NL (2013)

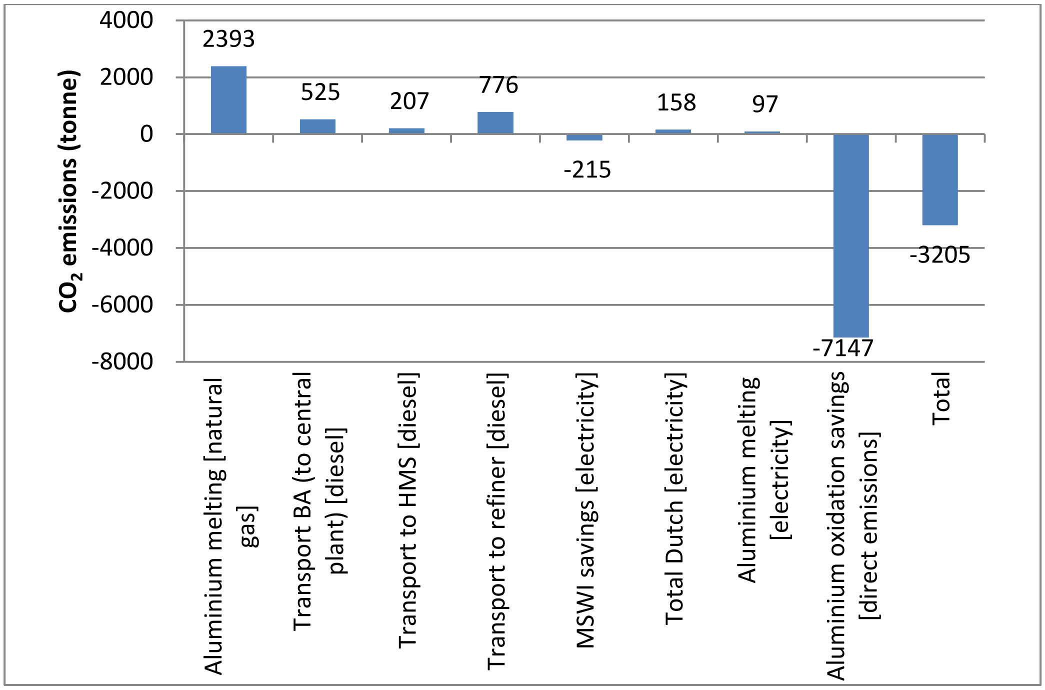

Figure 27: CO$_2$ emissions in the recovering and recycling of aluminium including aluminium oxidation from bottom ash

CO$_2$ emission including aluminium losses

In 2012, the assessed aluminium losses were 27.7 ktonne, originating from 41.2 ktonne aluminium present in the MSW, while 13.5 ktonne of aluminium was recycled into semi-finished products. This leads to a ratio of losses/recycled of 2.05. In other words, for every kg of recycled aluminium, 2.05 kg are lost in the system, either because they are not recovered from the bottom ash or due to oxidation or other losses during the recycling process. Assuming that the aluminium losses are replaced with primary aluminium produced in Europe, additional CO$_2$ emissions will occur due to this production. According to the EAA (2013) the production of primary aluminium in Europe emits 7 703 kg CO$_2$ per tonne aluminium ingots. This means that by replacing the 27.7 ktonne aluminium, 213.5 ktonne CO$_2$ are emitted. The details are shown in table 28.

Table 28: CO$_2$ emissions due to aluminium replacement with primary aluminium produced in Europe

Description:	Value:
Aluminium losses in supply chain (ktonne)	27.7
CO$_2$ intensity primary aluminium produced in Europe (kg/tonne)	7 703[63]
CO$_2$ emissions due to replacement of aluminium (ktonne)	**213.5**

In table 29 these emissions are included, together with the emissions of the recovery and recycling system and the savings due to oxidation. In figure 28 the distribution of the CO$_2$ emissions is shown over the various parameters. As can be seen, the replacement of aluminium dominates the CO$_2$ emissions.

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[63] Source: EAA (2013)

Table 29: CO_2 emissions and CO_2 intensity of the recovery and recycling process including CO_2 savings due to oxidation and primary aluminium replacement

Description:	Value:
CO_2 emission in recovery and recycling of aluminium (ktonne)	**210.3**
Total aluminium recycled (ktonne)	13.5
CO_2 intensity (kg/tonne)	**15 551**

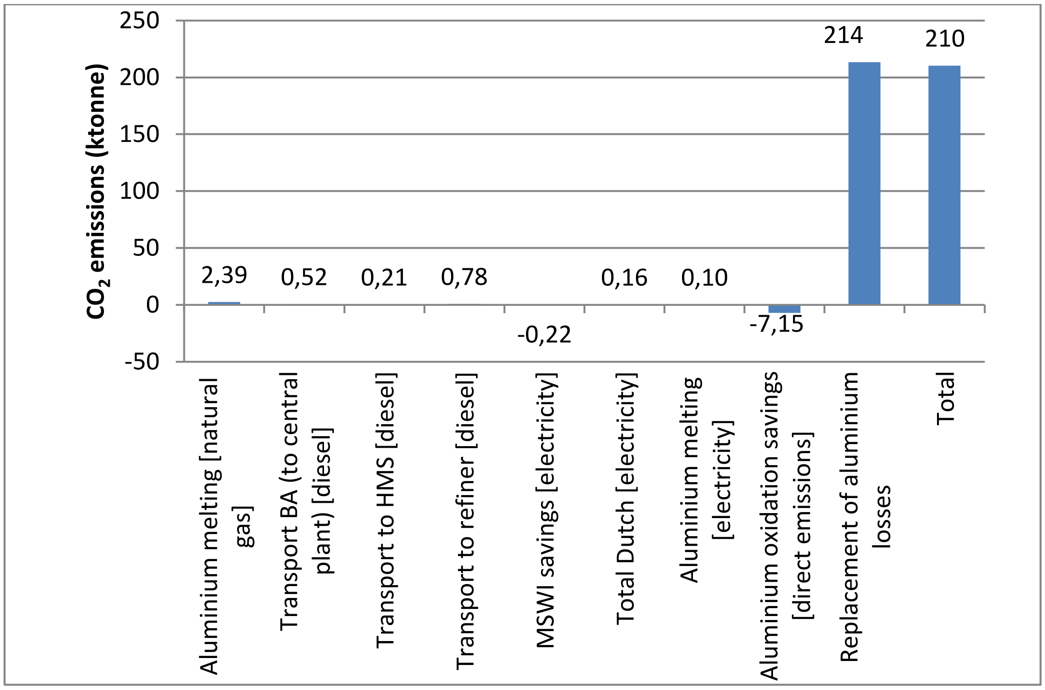

Figure 28: CO_2 emissions in the recovering and recycling of aluminium from bottom ash, including aluminium oxidation and replacement of losses

Overall CO_2 savings

The total CO_2 emissions due to recovery and recycling are 210.3 ktonne CO_2. However, this is still lower than the complete replacement of the 41.2 ktonne on aluminium. With the same emission factor provided by the EAA (2013), namely 7 703 kg/tonne, the total emissions for the production of 41.2 ktonne would be 317.7 ktonne CO_2. This means that the total CO_2 savings due to the recovery and recycling of aluminium from bottom ash are 107.4 ktonne CO_2 for 13.5 ktonne or 7 940 kg/tonne. The details of this analysis are shown in table 30.[64]

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[64] Note that these values are only valid for 13.5 ktonne recycled from 41.2 aluminium in MSW

Table 30: overall CO_2 emissions savings

Description:	Value:
Aluminium in MSW (ktonne)	41.2
CO_2 required to produce the full amount of primary aluminium (ktonne)	317.7
CO_2 emission in recovery and recycling of aluminium (ktonne)	210.3
CO_2 savings due to recovery and recycling system (ktonne)	**107.4**
Total aluminium recycled (ktonne)	13.5
CO_2 savings due to recovery and recycling system (kg/tonne)	**7 940**

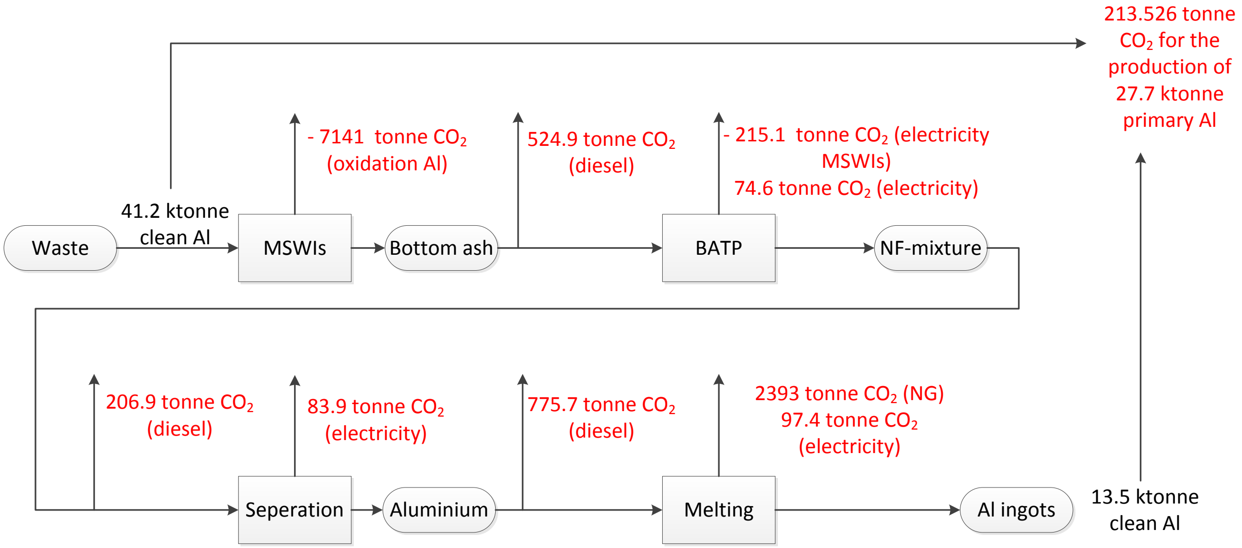
Comparing the CO_2 emission of aluminium from bottom ash with the recycling of old aluminium scrap, which has according to the EAA (2013) a CO_2 emission of 482 kg/ tonne, it is most likely that, due to the lower recycling rate of aluminium recovered from bottom ash, it will have more environmental impact, since the recycling factor for old scrap has to be less than 33.8 % in order to have an higher CO_2 emission. This also includes the CO_2 emissions for the replacement of primary aluminium. Depending on the area of application, the recycling rate is in most cases higher, as is shown in paragraph 7.3.

7.5. Conclusion

Looking at the CO_2 emissions and CO_2 intensities from primary and secondary aluminium, and the emissions from aluminium recovered and recycled from MSWI bottom ash, it can be concluded that the emissions of the recycling and recovering system are even lower (291.4 kg CO_2/tonne) than from new scrap. According to the EAA (2013) this emits 349 kg CO_2/tonne ingot. This is due to the fact that, for example, CO_2 emissions from the MSWI are not allocated to the production of electricity but to its primary task: the incineration of waste. Correcting this based on the energy produced by the MSWI, it would be lower as new scrap (319 kg CO_2/tonne), which is still a remarkable achievement. However, due to the low aluminium recovery from bottom ash the lower emission in the recycling process is lost, when the replacement of the losses by primary aluminium are included.

Applying the same calculation method for aluminium from bottom ash and including the CO_2 savings due to oxidation, the CO_2 emission factor even becomes negative, -237 kg CO_2/tonne. If the losses of 27.7 ktonne are also incorporated in the system, the emission factor goes up to 15 551 kg CO_2/tonne aluminium recovered, thereby still saving a total of 107.4 ktonne on CO_2 emissions compared to the complete replacement of the 41.2 ktonne aluminium in the MSW with primary aluminium or 7 940 kg/tonne. An overvieuw of the CO_2 emissions in the supply chain and by the replacement of primary aluminium is shown in figure 29.

Figure 29: overview of the CO_2 emissions throughout the supply chain in 2012



Chapter 8: Discussion

8.1. Critical assessment of various input parameters and assumptions

Applying ADR

In 2012, the use of ADR was limited to two plants, which treated approximately a third of the Dutch bottom ash. However, the application of ADR has increased since 2012, and it is reasonable to assume the application of ADR will increase in the coming years. By increasing the application of ADR or other new technologies, the metal losses will decrease.

Fuel mix used by aluminium refiners

In the analysis it is assumed that refiners only use natural gas for firing the rotary drum furnaces. However, to a small extend other fossil fuels are also used by the refiners, according to the EAA (2013). These are most likely not used to fire the RDFs, but it cannot be excluded either. The use of another type of fossil fuel will affect the CO_2 emission, but since this is limited to a small extend, the influences will be limited.

Oxidation of aluminium

In the analysis, the energy released due to oxidation is based on the reaction into aluminium oxide(corundum) within the furnace. However, since the reaction also partially occurs with hydroxide for example, this may not be totally valid. The reaction of aluminium to corundum (Al_2O_3) generates the most energy, while the reaction to aluminium oxide hydroxide ($AlO(OH)$) and aluminium hydroxide ($Al(OH)_3$ generates less energy within the furnace. Of course other reactions can occur. Therefore, the actual amount of energy released is uncertain and likely to be less, however to what extend is unknown. This not only affects the energy balance but also the mass balance since the aluminium losses are now deducted from the aluminium in the waste.

Amount of aluminium in waste

The amount of aluminium in waste is in this analysis based on the results of sorting analysis. However, these analysis are based on samples and waste is heterogeneous, therefore the amount of aluminium in waste that is incinerated is uncertain. The data used is the best available option, due to lack of more reliable date.

Primary and alloyed aluminium

In the analysis primary aluminium is used to indicate the savings made by the recovery of aluminium from bottom ash, but the amount of aluminium recovered is used in alloys, which may affect the amount of savings. On the other hand the recovered aluminium is mainly used in DIN 226 alloys where the additions of alloy agents is limited to a minimum. This implies that the recovered aluminium can be used directly in the production of new semi-finished products.

Decreasing amounts of waste

It is most likely that in the coming decades the amount of waste will change in composition and amount, due to the enhanced focus on circular economy, potentially supported by legislation. This may influence the emissions and emission savings concerning the recovery and recycling of aluminium from MSWI bottom ash.

Collection system

In the Netherlands aluminium, in most cases, ends up in the municipal solid waste. Countries such as Germany and the Scandinavian countries use a deposit system for used beverage cans (EAA, 2011). However, according to Muchova (2010) the composition of German bottom ash has a similar composition. Although Germany and the Scandinavian countries have a higher recycling factor for aluminium used beverage cans compared to the Netherlands (85 % vs. 91-96 %, (EAA, 2011)), this does not result in a significantly lower amount of aluminium in bottom ash. The aluminium use per capita however is higher for Sweden and Germany, this however not the case for Denmark and Norway.

8.2. Uncertainty & sensitivity analysis

In order to assess the uncertainty in the results, an uncertainty analysis should be performed. However, since the uncertainty for most of the input data is unknown, a quantitative assessment of the uncertainty is not possible.

Therefore, a qualitative analysis is made based on the (expected) quality of the data available in order to use a appropriated variation in the sensitivity analysis. This is only done from parameters from which can be expected that they significantly affect the end result.

Based on the figures 26-28, from which the contribution of individual process can be derived, it is assess whether or not a parameter could affect the end result. The level of uncertainty in these parameter is determined based on the origin of the data and the uncertainty qualitative or quantitative described in the literature.

Non-Ferrous metal recovered from bottom ash

The amount of non-ferrous metals recovered from bottom ash could play an important role in the end result since it affects not only the amount of aluminium which has to be treated in the total supply chain but also the recovery factor and with that the amount additional primary aluminium needed to replace the losses in the system. The amount of non-ferrous metals recovered is reported by the Dutch Wase Management Association and is based on data from the Dutch MSWIs It is expected that the uncertainty in this value is limited. However, the degree of uncertainty might be higher for the deduction of impurities and the aluminium concentration in this mix. Therefore, an range of ± 50 % will be used in the sensitivity analysis to examine the effect on the end result.

CO_2 emission primary aluminium

Another parameter which could have an high effect on the end results is the CO_2 emission factor for primary aluminium since the replacement of aluminium dominates the end result. These data are reported by the EAA and are average values for primary aluminium from which a limited uncertainty is expected. Therefore, an range of ± 10 % will be used in the sensitivity analysis to examine the effect on the end result.

Natural gas use

The natural gas use, required to melt the aluminium may also have an impact on the total emissions. The data origins from two books, which describe the field of aluminium recycling Schmitz (2006) & Schleslinger (2007). It is expected that they have limited uncertainty. Therefore, an range of ± 10 % will be used in the sensitivity analysis to examine the effect on the end result.

Diesel use

Transport has also an impact on the end results, Looking at the transport in this supply chain, than can be concluded that transport by truck has the largest part in the emissions of transport. Data regarding fuel use and CO_2 emission where retrieved from SKOA (2011) en it is expected that there is limited uncertainty in this value. However, due to differences in the truck fleet, the uncertainty is expected to be of a modest level. Therefore, a range of ± 20 % will be used in the sensitivity analysis to examine the effect on the end result.

Oxidation factor

The oxidation factor has influence on the amount of aluminium, which could potentially be recovered and also influences the total amount of energy generated due to the oxidation in the furnace. The data was retrieved from Tauw (2012). Since the degree of uncertainty is expected to be high an range of ± 50 % will be used in the sensitivity analysis to examine the effect on the end result.

Aluminium in non-ferrous mixture

The percentage aluminium in the recovered non-ferrous mixture influences the total amount of aluminium and therewith the amount of energy needed in the supply chain but also the amount of aluminium that need to be produced to compensate the losses in the system. The amount of aluminium is determined based on experts opinions and literature, therefore it is expected that the uncertainty is limited. Therefore, an range of ± 10 % will be used in the sensitivity analysis to examine the effect on the end result.

Based on the parameters and their range as described before a sensitivity analysis is performed. The results from this analysis can be found in figure 30.

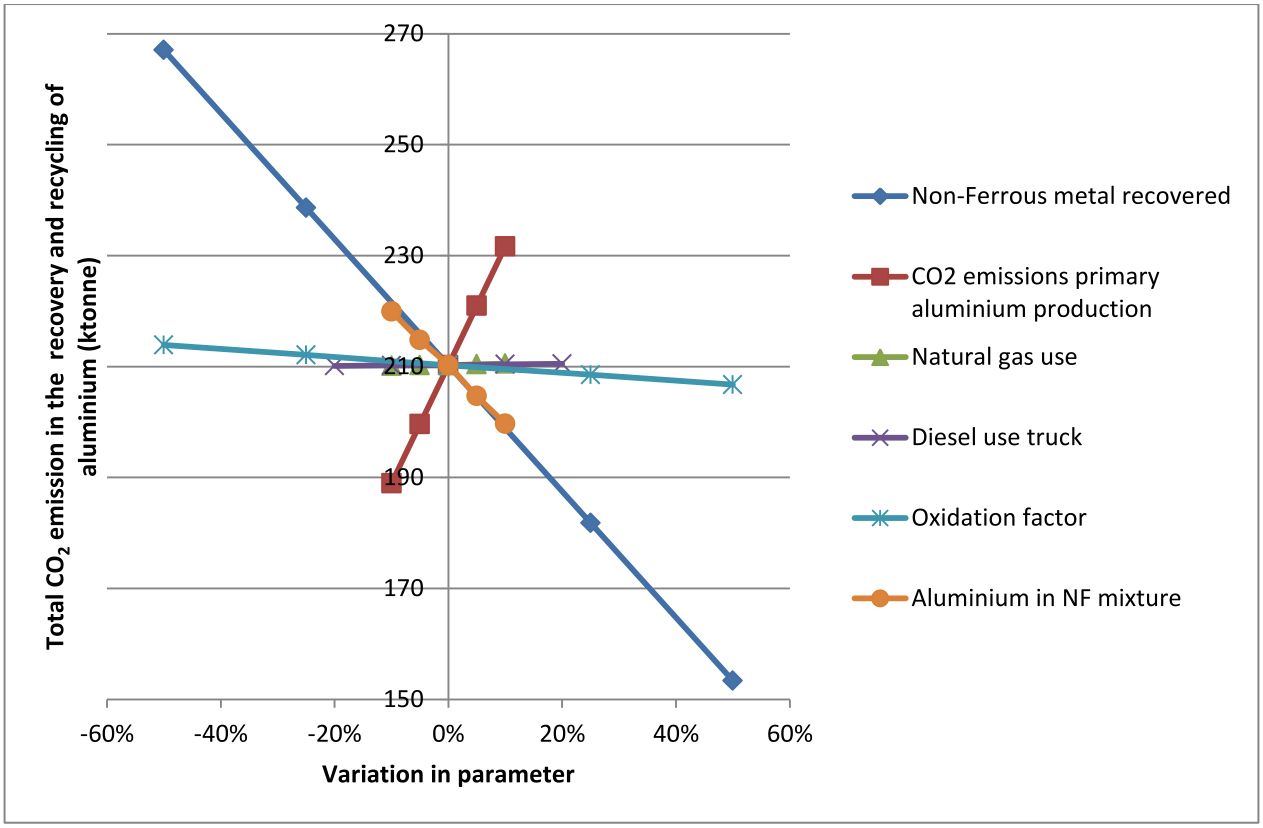


Figure 30: sensitivity analysis (of the most sensitive parameters) for system 3

Due to the domination of the CO_2 emissions from primary aluminium in the end result, three parameters have a high impact on the sensitivity. The first of them is of course the emission factor for the production of primary aluminium itself. The other two affect both the same variable, namely the amount of aluminium which has to be replaced with primary aluminium. This is however less the case for the oxidation factor, This is due to the fact that in the calculations only the potential of recoverable aluminium is affected and not the amount of non-ferrous, an thus aluminium, recovered from bottom ash. The effect is therefore attributable to the additional energy release without extra CO_2 emissions. The energy use from transport by truck or for melting aluminium have a marginal effect on the CO_2 emissions.

Sensitivity analysis of the allocation

Besides the input parameters, the allocation of energy and CO_2 emissions to certain streams also has an impact on the sensitivity of the end result. For instance the transport of bottom ash to the central treatment plant by ship, where the metals are recovered. In the analysis all the energy used for transporting the bottom ash is allocated to the recovered metals, but it can be argued that the bottom ash, which will be used for civil engineering applications later on, is partly transported in the direction where it will be used. Since this depends highly on the site of application, an equal allocation based on mass is made for bottom ash and the recovered metals. This allocation lowers the CO_2 emissions by 451.4 tonne up to 209.9 ktonne, which has little effect on the total emissions, which is in line with the sensitivity analysis for the input parameters.

Another allocation factor that somewhat influences the end result is the allocation of CO_2 emission savings, due to the electricity production by MSWIs, to the electricity production by other means. It is assumed that the production of electricity by MSWIs replaces other electricity production and thereby saves CO_2 emissions. However, if the CO_2 emissions due to the electricity production are included either for the non-biogenic part, where it is assumed that the biogenic part has no emissions, or for the total the final emission increase for the non-biogenic part with 379.6 tonne to 210.7 ktonne CO_2 or with 685 tonne to 211.0 ktonne CO_2 for the total waste. The detailed results are presented in table 31.

Table 31: effect of allocations on end result

	CO_2 emissions due recovering and recycling (ktonne)
Final result	210.3
Results with other allocation	
Allocation to bottom ash during shipment	209.9
Including CO_2 emissions MSWI electricity non-biogenic part (0.34 kg/kWh)	210.7
Including total waste CO_2 emissions MSWI electricity (0.96 kg/kWh)	211.0

Chapter 9: Conclusion

The total process, from the recovering of aluminium from MSWI bottom ash until the final recycling of aluminium into semi-finished products, is analysed and described in the previous chapters, in order to assess the total CO_2 emissions in en in-between these processes.

It is assessed that a total of 41.2 ktonne metallic aluminium has been incinerated as part of the waste in 2012. From the remaining bottom ash 14.8 ktonne clean aluminium is recovered, while 7.2 ktonne of aluminium is lost in the incineration process mainly due to oxidation. It is estimated that 19.2 ktonne of aluminium is not yet recovered in 2012.

During the recycling of the recovered aluminium, 1.3 ktonne is lost in the separation of aluminium from the non-ferrous mixture, and melting and casting into the semi-finished products. The details of the mass balance of aluminium throughout the supply chain are shown in figure 31.

From these results an overall recycling rate of 33 % is derived, while there is still a large potential for additional aluminium recovery from bottom ash. The recycling factor is considerably lower than for instance the official recycling rate of 67 % in 2010 (EAA, 2013) in Europe for beverage cans. However, this is not fully comparable since the aluminium recovered is not only from aluminium cans. Over 2012, it is assessed that 47 % of the aluminium present in waste is not yet recovered. This is mainly due to the small size of the aluminium particles and the processability of bottom ash, which makes it not yet recoverable.

Due to the application of Advanced Dry Recovery and potentially other technologies in the future, smaller particles can be recovered and thereby increase the efficiency for recovering aluminium and other non-ferrous metals. However, ADR is only applied at two bottom ash treatment plants in 2012, where approximately 28 % of the Dutch bottom ash is treated. So the effect in this analysis is still limited. However, it is likely that, due to the increased installation of advanced technologies in bottom ash treatments plants, the amount of aluminium recovered and therewith the recycling factor will increase over the next years. If ADR is used for the bottom ash of all Dutch MSWIs and keeps the same recovery it is estimated that the amount of aluminium recycled will increase with approximately 5 ktonne which gives an recycling factor of 45 %. Besides the application of advanced technologies there seems also room for improvement with the regular recovery since the estimated recovery factors, based on the average aluminium concentration and average aluminium concentration in NF, varies between 8-45 %. However, it could be argued that these average values used to calculated done apply to a specific MSWI due for example different waste composition. This does however not justify such a difference in the recovery factor.

The effects of oxidation in the Netherlands due to the incineration seem limited with 10-20 % oxidation losses, compared with oxidation grades reported in Italy for example. There are still uncertainties in this area, but at the same time it must be concluded that oxidation is the second biggest loss of metallic aluminium in this process, after the losses of non-recovered aluminium. The oxidation of aluminium limits the recycling factor to a maximum of 82.5 %. The losses in the remaining supply chain are confined to 3 % of the total losses.

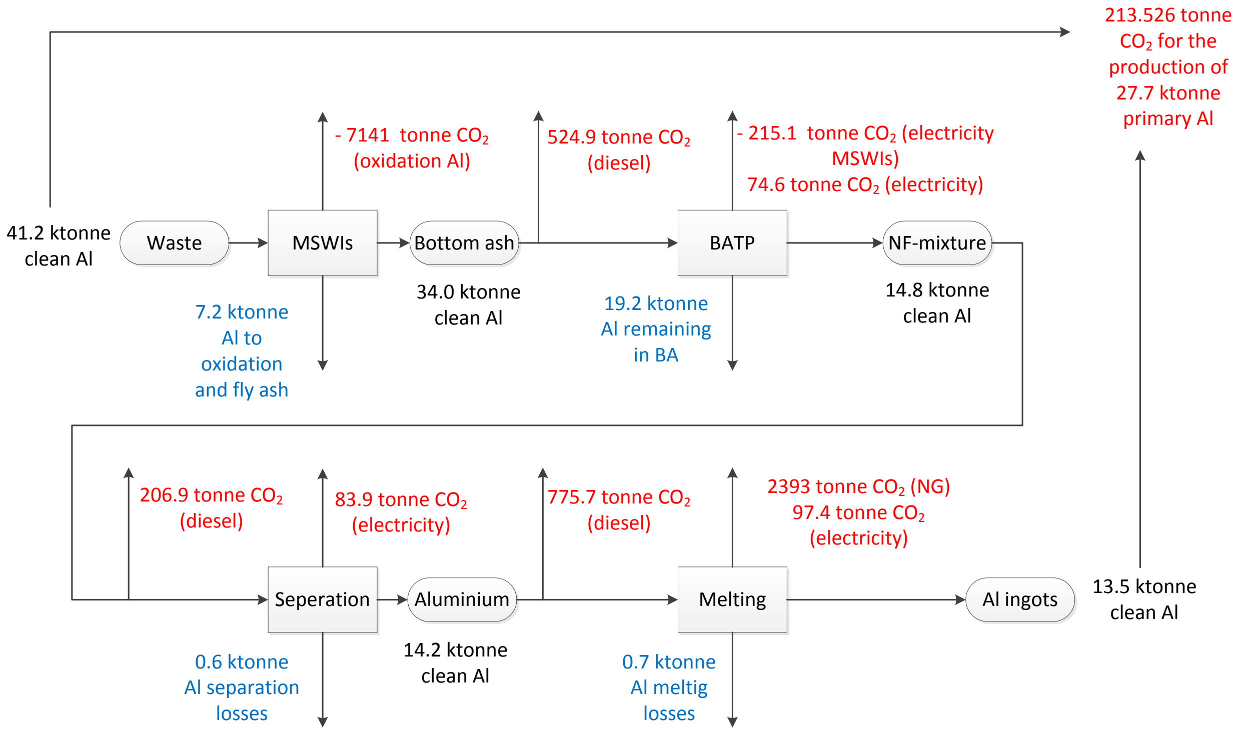
The 13.5 ktonne aluminium that is recycled will be mainly alloyed with other scrap material into DIN 226 alloys, which are used for castings in engine parts.

The CO_2 emissions or abated emissions during the recycling do not only include the emissions caused in the supply chain, but also the emission savings due to aluminium oxidation in the incinerator and the replacement of aluminium losses by primary aluminium. Including this, a total of 210.3 ktonne of CO_2 is emitted in 2012. In figure 31 an overview is provided with the amounts of CO_2 emitted in the supply chain and by the replacement of primary aluminium.

With the CO_2 emission of 210.3 ktonne, the recovery of aluminium from bottom ash still emits less CO_2 than if the total amount of aluminium present in waste would have been replaced by primary aluminium, which is for 41.2 ktonne 317.7 ktonne CO_2. For 2012, it is assessed that the recovery of aluminium from bottom ash saves 34 % or 7 940 kg CO_2/tonne aluminium of emissions, which would occur if the aluminium was not recovered.

The CO_2 emission saving of 34 % is a lot less than the often-used comparison with regular scrap, where up to 97 % less CO_2 is emitted than with the production of primary aluminium.

Figure 31: overview of the mass balance of aluminium and CO_2 emissions throughout the supply chain in 2012



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Annex I: Calculations

Chapter 3

Annex 1 1: calculation of the amount of aluminium in incinerated waste

$$\boldsymbol{Aluminium\ in\ incinerated\ waste} = (\,Dutch\ waste \cdot MSW\ ratio \cdot Al\ concentration\ MSW) + (\,Dutch\ waste \cdot NPRIW\ ratio \cdot Al\ concentration\ NPRIW) + (\,Dutch\ waste \cdot SW\ ratio \cdot Al\ concentration\ SW) + (\,imported\ waste \cdot MSW\ ratio \cdot Al\ concentration\ MSW) + (\,imported\ waste \cdot NPRIW\ ratio \cdot Al\ concentration\ NPRIW) + (\,imported\ waste \cdot SW\ ratio \cdot Al\ concentration\ SW) = (\,6\ 436\ ktonne\ \cdot 55\% \cdot 0{,}8\%) + (\,6\ 436\ ktonne \cdot 6\% \cdot 0.08\%) + (\,6\ 436\ ktonne \cdot 36\% \cdot 0{,}3\%) + (\,1\ 035\ ktonne \cdot 55\%\ \cdot 0.8\%\,) + (1\ 035\ ktonne \cdot 6\% \cdot 0.08\%) + (1\ 035\ ktonne\ \cdot 36\% \cdot 0.3\%) = \mathbf{41.2}\ \boldsymbol{ktonne}$$

Annex 1 2: calculation of the amount of aluminium which can potentially be recovered

$$\begin{aligned}\boldsymbol{Potential\ recoverble\ aluminium} &\\ &= Aluminium\ in\ incinerated\ waste\\ &- (Aluminium\ in\ incinerated\ waste \cdot Overall\ oxidation\ grade)\\ &- (Aluminium\ in\ incinerated\ waste \cdot Aluminium\ to\ fly\ ash)\\ &- \ (Aluminium\ in\ incinerated\ waste \cdot mass\ fraction\ aluminium\ 0-2\ mm \cdot oxidation\ rate\ 0\\ &- 2\ mm)\\ &= 41.2\ ktonne - (41.2\ ktonne \cdot 15\ \%) - (41.2\ ktonne \cdot 0.2\ \%) - (41.2\ ktonne \cdot 23\ \% \cdot 10\ \%)\\ &= \mathbf{34.0}\ \boldsymbol{ktonne}\end{aligned}$$

Annex 1 3: calculation of the energy contribution due to aluminium oxidation:

$$\begin{aligned}\boldsymbol{Energy\ contribution\ due\ to\ oxidation\ aluminium} &= aluminium\ oxidezed \cdot enthalpy\ of\ combustion\\ &= 6.2\ ktonne \cdot 31.05\frac{MJ}{kg} = \mathbf{0.19}\ \boldsymbol{PJ}\end{aligned}$$

Annex 1 4: calculation of the energy contribution of aluminium oxidation:

$$\boldsymbol{Energy\ contribution\ of\ aluminium\ oxidation} = \frac{Energy\ contribution\ due\ to\ oxidation\ aluminium}{Total\ energy\ due\ to\ combustion}$$

$$= \frac{0{,}19\ PJ}{71.92\ PJ} = \mathbf{0.27\%}$$

Chapter 4

Annex 1 5: calculation of the amount of non-ferrous metals recovered from MSWI bottom ash

$$\begin{aligned}\boldsymbol{Non-ferrous\ metals\ recoverd\ from\ bottom\ ash} &= clean\ NF/(1 - impurity\ factor)\\ &= 25.2\ ktonne/(1-0.1) = \mathbf{28.0}\ \boldsymbol{ktonne}\end{aligned}$$

Annex 1 6: calculation of the amount of aluminium recovered from MSWI bottom ash

$$\boldsymbol{Aluminium\ recoverd\ from\ bottom\ ash} = NF\ \ \cdot aluminium\ content\ \ = 28.0\ ktonne \cdot 60\% = \mathbf{16.8}\ \boldsymbol{ktonne}$$

Annex 1 7: calculation of the amount of clean aluminium recovered from MSWI bottom ash

$$\begin{aligned}\boldsymbol{Clean\ aluminium\ recoverd\ from\ bottom\ ash} &= NF\ \cdot \frac{aluminium\ content}{(1 - impurity\ content)} = 25.2\ ktonne \cdot \frac{60}{1-0.1}\\ &= \mathbf{14.8}\ \boldsymbol{ktonne}\end{aligned}$$

Annex 1 8: calculation of the recovery factor of clean aluminium with respect to aluminium in bottom ash

$$\boldsymbol{Recovery\ factor\ of\ clean\ aluminium\ with\ respect\ to\ aluminium\ in\ bottom\ ash}$$
$$= \frac{Clean\ aluminium\ recovered}{Potential\ recoverable\ aluminium\ from\ bottom\ ash} = \frac{14.8\ ktonne}{34.0\ ktonne} = \mathbf{43\%}$$

Annex 1 9: calculation of the recovery factor of clean aluminium with respect to aluminium in waste

$$\boldsymbol{Recovery\ factor\ of\ clean\ aluminium\ with\ respect\ to\ aluminium\ in\ bottom\ ash}$$
$$= \frac{Clean\ aluminium\ recovered}{\boldsymbol{Aluminium\ in\ incinerated\ waste}} = \frac{14.8\ ktonne}{41{,}2\ ktonne} = \mathbf{36\%}$$

Annex 1 10: calculation of the amount of diesel used for the recovery of aluminium

$$\boldsymbol{Amount\ of\ diesel\ used}$$
$$= (transport\ distance\ for\ metals \cdot diesel\ use\ barge) + \left(\frac{diesel\ use\ internal\ trasnport \cdot amount\ of bottom\ ash}{2}\right)$$
$$= (68\ 460\ 000\ tonne \cdot km \cdot 0.022\ l/tonne \cdot km) + \left(\frac{0.29\ l/tonne \cdot 1\ 696\ ktonne \cdot 1000}{2}\right)$$
$$= \mathbf{1\ 768\ 783}\ \boldsymbol{liter\ diesel}$$

Annex 1 11: calculation of the energy used on diesel

$$\boldsymbol{Energy\ use\ on\ diesel} = ammount\ of\ diesel \cdot calorific\ value = 1\ 768\ 783\ l \cdot 36\ MJ/l = \mathbf{63\ 676}\ \boldsymbol{GJ}$$

Annex 1 12: calculation of the electricity use of the bottom ash treatment plants

$$\boldsymbol{Total\ electricity\ use\ for\ BATP} = Electricity\ use\ \cdot amount\ of\ bottom\ ash = 3{,}5\ \ kWh/tonne \cdot 1\ 696\ ktonne$$
$$= \mathbf{5\ 934}\ \boldsymbol{MWh}$$

Annex 1 13: Diesel use per tonne of recovered material

$$\boldsymbol{Diesel\ used\ per\ tonne\ recover\ material} = \frac{diesel\ used}{Ferrous + NF} = \frac{63\ 676\ GJ}{123.3\ ktonne + 28.0\ ktonne}$$
$$= 420.83\ MJ/tonne$$

Annex 1 14: electricity use per tonne of recovered material

$$\boldsymbol{Electricity\ used\ per\ tonne\ recover\ material} = \frac{electricity\ used}{Ferrous + NF} = \frac{5\ 934\ MWh}{123.3\ ktonne + 28.0\ ktonne}$$
$$= \mathbf{39.22}\ \boldsymbol{kWh/tonne}$$

Annex 1 15: allocation of diesel to aluminium

$$\boldsymbol{Diesel\ used\ for\ recoverd\ aluminium} = diesel\ used\ per\ tonne \cdot ammount\ of\ aluminium\ recoverd$$
$$= 420.83\ MJ/tonne \cdot 16.8\ ktonne = \mathbf{7\ 064}\ \boldsymbol{GJ}$$

Annex 1 16: allocation of electricity to aluminium

$$\boldsymbol{Electricity\ used\ for\ recoverd\ aluminium}$$
$$= Electricity\ used\ per\ tonne \cdot ammount\ of\ aluminium\ recoverd$$
$$= 39.62\ kWh\ /tonne\ \ \cdot 16.8\ ktonne = \mathbf{658}\ \boldsymbol{MWh}$$

Chapter 5

Annex 1 17: calculation of the total input separation techniques

$$\boldsymbol{Total\ input\ separtion\ techniques} = clean\ input\ separation\ techniques/(1 - impurtiy\ factor)$$
$$= 22.19\ ktonne/(1 - 10\%) = \mathbf{24.66}\ \boldsymbol{ktonne}$$

Annex 1 18: calculation of clean non-ferrous metal input HMS:

$$\boldsymbol{Clean\ NF\ input\ HMS} = Clean\ NF\ input - clean\ NF\ input\ KGS - clean\ NF\ input\ MDS$$
$$= 22.19 ktonne - 2.46\ ktonne\ (Annex\ IV) - 0\ ktonne = \mathbf{19.73\ ktonne}$$

Annex 1 19: calculation of non-ferrous input HMS:

$$\boldsymbol{NF\ input\ HMS} = clean\ input\ HMS/(1 - impurtiy\ factor) = 19.73\ ktonne/(1 - 10\%) = \mathbf{21.92\ ktonne}$$

Annex 1 20: calculation of the aluminium output by HMS:

$$\boldsymbol{Aluminium\ output\ HMS} = clean\ input\ NF\ HMS \cdot aluminium\ content\ clean\ NF \cdot HMS\ efficiency$$
$$= 19.73\ ktonne \cdot 67\% \cdot 96\% = \mathbf{12.63\ ktonne}$$

Annex 1 21: calculation of the non-ferrous input KGS:

$$\boldsymbol{NF\ input\ KGS} = clean\ input \frac{KGS}{(1 - impurtiy\ factor)} = 2.46 \frac{ktonne}{(1 - 10\%)} = \mathbf{2.73\ ktonne}$$

Annex 1 22: calculation aluminium output KGS:

$$\boldsymbol{Aluminium\ output\ KGS} = clean\ input\ NF\ KGS \cdot aluminium\ content\ clean\ NF \cdot KGS\ efficiency$$
$$= 3.05\ ktonne \cdot 67\% \cdot 98\% = \mathbf{1.61\ ktonne}$$

Annex 1 23: electricity use HMS

$$\boldsymbol{Electricity\ use\ HMS} = input\ NF\ HMS \cdot energy\ use\ HMS = 21.92\ ktonne \cdot 13.2 \frac{kWh}{tonne} = \mathbf{289.4\ MWh}$$

Annex 1 24: electricity use KGS

$$\boldsymbol{Electricity\ use\ KGS} = input\ NF\ KGS \cdot energy\ use\ HMS = 2.73\ ktonne \cdot 15.0 \frac{kWh}{tonne} = \mathbf{41.0 MWh}$$

Annex 1 25: total electricity use related to aluminium:

$$\boldsymbol{Total\ electricity\ use\ related\ to\ aluminium} = \frac{Total\ aluminium\ recoverd}{NF\ input} \cdot Total\ electricity\ use$$
$$= \frac{14.2\ ktonne}{24.7\ ktonne} \cdot 330.4\ MWh = \mathbf{191\ MWh}$$

Chapter 6

Annex 1 26: amount of aluminium in semi-finished product

$$\boldsymbol{Aluminium\ in\ semi\ finished\ product} = aluminium\ to\ refiner \cdot (1 - melting\ losses)$$
$$= 14.2\ ktonne \cdot (1 - 5\%) = \mathbf{13.5\ ktonne}$$

Annex 1 27: total recycling factor:

$$\boldsymbol{Total\ recyling\ fator} = \frac{aluminium\ in\ waste}{aluminium\ in\ SFP} = \frac{41.2\ ktonne}{13.5\ ktonne} = \mathbf{33}\%$$

Annex 1 28: natural gas use during melting

$$\boldsymbol{Gas\ use} = (NG\ use\ slag\ treatment\ \cdot aluminium\ produced) + (NG\ use\ melting \cdot aluminium\ produced)$$
$$= \left(170\ {}^{\frac{kWh}{tonne}}\!\Big/_{tonne\ output} \cdot 13.5\ ktonne\right) + \left(700\ {}^{\frac{kWh}{tonne}}\!\Big/_{tonne\ output} \cdot 13.5\ ktonne\right)$$
$$= \mathbf{42\ 359}\ \boldsymbol{GJ}$$

Annex 1 29: electricity use during melting

$$\boldsymbol{Electricity\ use}$$
$$= (electricity\ use\ slag\ treatment\ \cdot aluminium\ produced)$$
$$+ (electricity\ use\ melting \cdot aluminium\ produced)$$
$$= \left(2.5\ {}^{\frac{kWh}{tonne}}\!\Big/_{tonne\ output} \cdot 13.5\ ktonne\right) + \left(10\ {}^{\frac{kWh}{tonne}}\!\Big/_{tonne\ output} \cdot 13.5\ ktonne\right)$$
$$= \mathbf{169}\ \boldsymbol{MWh}$$

Annex 1 30: diesel use for transport to refiner

$$\boldsymbol{Diesel\ use} = average\ distance\ to\ refiner \cdot ammount\ of\ aluminium\ to\ refiner \cdot diesel\ use\ truck$$
$$\cdot calorific\ value\ diesel = 500\ km\ \cdot 14.2\ ktonne \cdot 0.04 \frac{l}{tonne \cdot km} \cdot 36 \frac{MJ}{l} = \mathbf{10\ 440}\ \boldsymbol{GJ}$$

Chapter 7

Annex 1 31: CO_2 emissions due to natural gas

$$\boldsymbol{CO_2\ emission\ due\ to\ natural\ gas} = Total\ natural\ gas\ use\ \cdot emission\ factor\ natural\ gas$$
$$= 42\ 359\ GJ \cdot 56.5 \frac{kg}{GJ} = \mathbf{2\ 393\ 272}\ \boldsymbol{kg}$$

Annex 1 32: CO_2 emissions due to diesel use

$$\boldsymbol{CO_2\ emission\ due\ to\ diesel} = Total\ diesel\ use\ \cdot emission\ factor\ diesel$$
$$= (10\ 440\ GJ + 2\ 785\ GJ + 7\ 064\ GJ) \cdot 74.3 \frac{kg}{GJ} = \mathbf{1\ 507\ 471}\ \boldsymbol{kg}$$

Annex 1 33: CO_2 emissions savings due to electricity use produced by MSWI

$$\boldsymbol{Emission\ savings\ due\ to\ electricity\ used\ produced\ by\ MSWI}$$
$$= Electricity\ used\ for\ bottom\ ash\ treatment\ plant$$
$$\cdot (1 - electricity\ not\ produced\ at\ MSWI)\ emission\ factor\ of\ electricity\ replaced$$
$$= \ 658\ MWh \cdot (1 - 25.7\%) \cdot 0.44 \frac{kg}{kWh} = \mathbf{215\ 123}\ \boldsymbol{kg}$$

Annex 1 34: CO_2 emissions due to electricity use German refiners

$$\boldsymbol{Emissions\ electricity\ use\ refiners} = Electricity\ used\ by\ refiners \cdot emission\ factor\ Germany$$
$$= 169\ MWh \cdot 0.576 \frac{kg}{kWh} = \mathbf{97\ 377}\ \boldsymbol{kg}$$

Annex 1 35: CO_2 emissions due to electricity use in the Netherlands

$$\boldsymbol{Emissions\ electricity\ in\ the\ Netherlands} = Dutch\ electricity\ use\ \cdot Dutch\ emission\ factor$$
$$= 360\ MWh \cdot 0.44 \frac{kg}{kWh} = \mathbf{158\ 498}\ \boldsymbol{kg}$$

Annex 1 36: total emissions due to electricity use

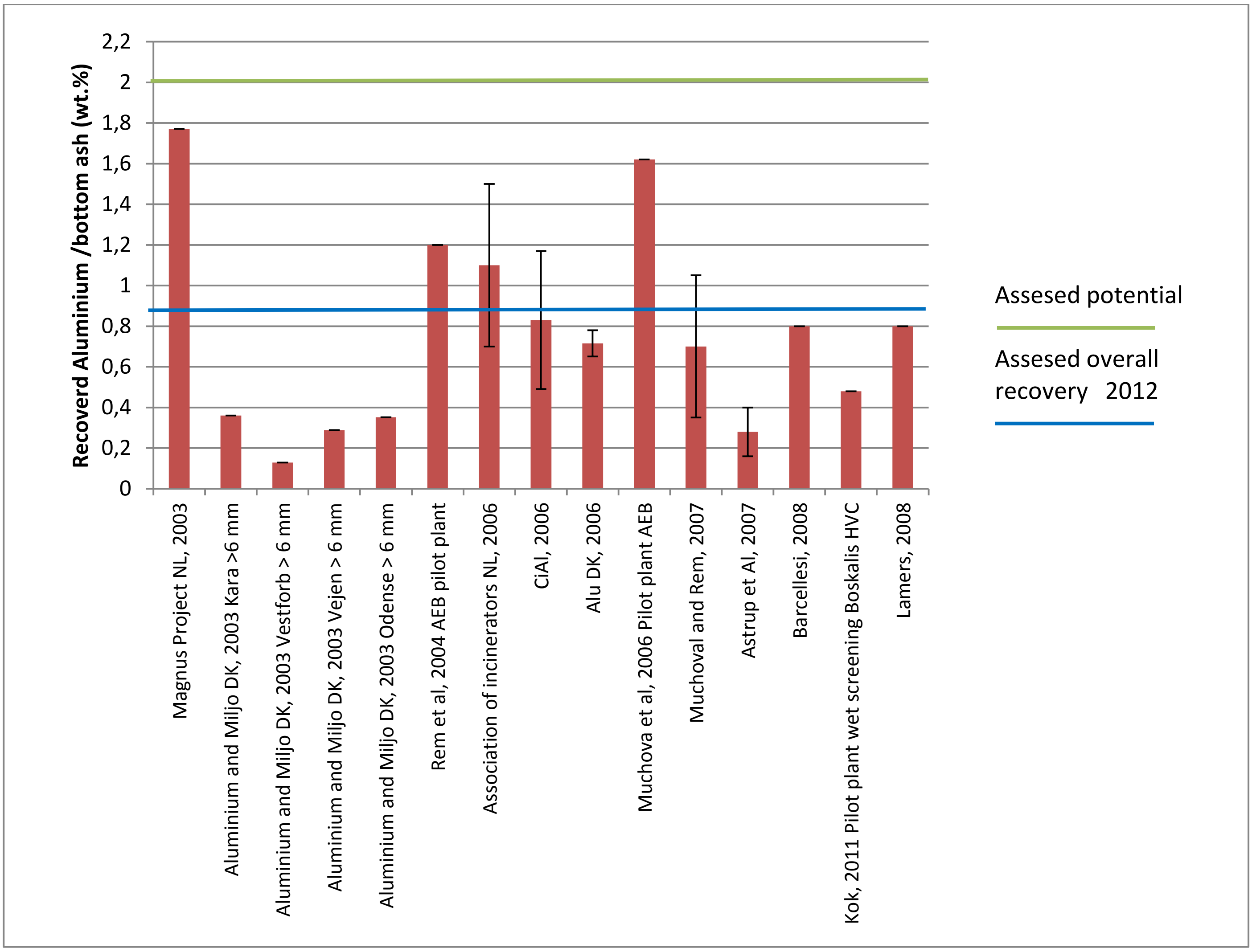
$$\begin{aligned}\boldsymbol{Total\ electricity\ emissions}\\ &= Emissions\ electricity\ in\ the\ Netherlands + Emissions\ electricity\ use\ refiners\\ &- Emission\ savings\ due\ to\ electricity\ used\ produced\ by\ MSWI\\ &= 158\,498\ kg + 97\,377\ kg\ - 215\,123\ kg = \mathbf{40\,752}\ \boldsymbol{kg}\end{aligned}$$

Annex II: Aluminium recovery from bottom ash reported in literature

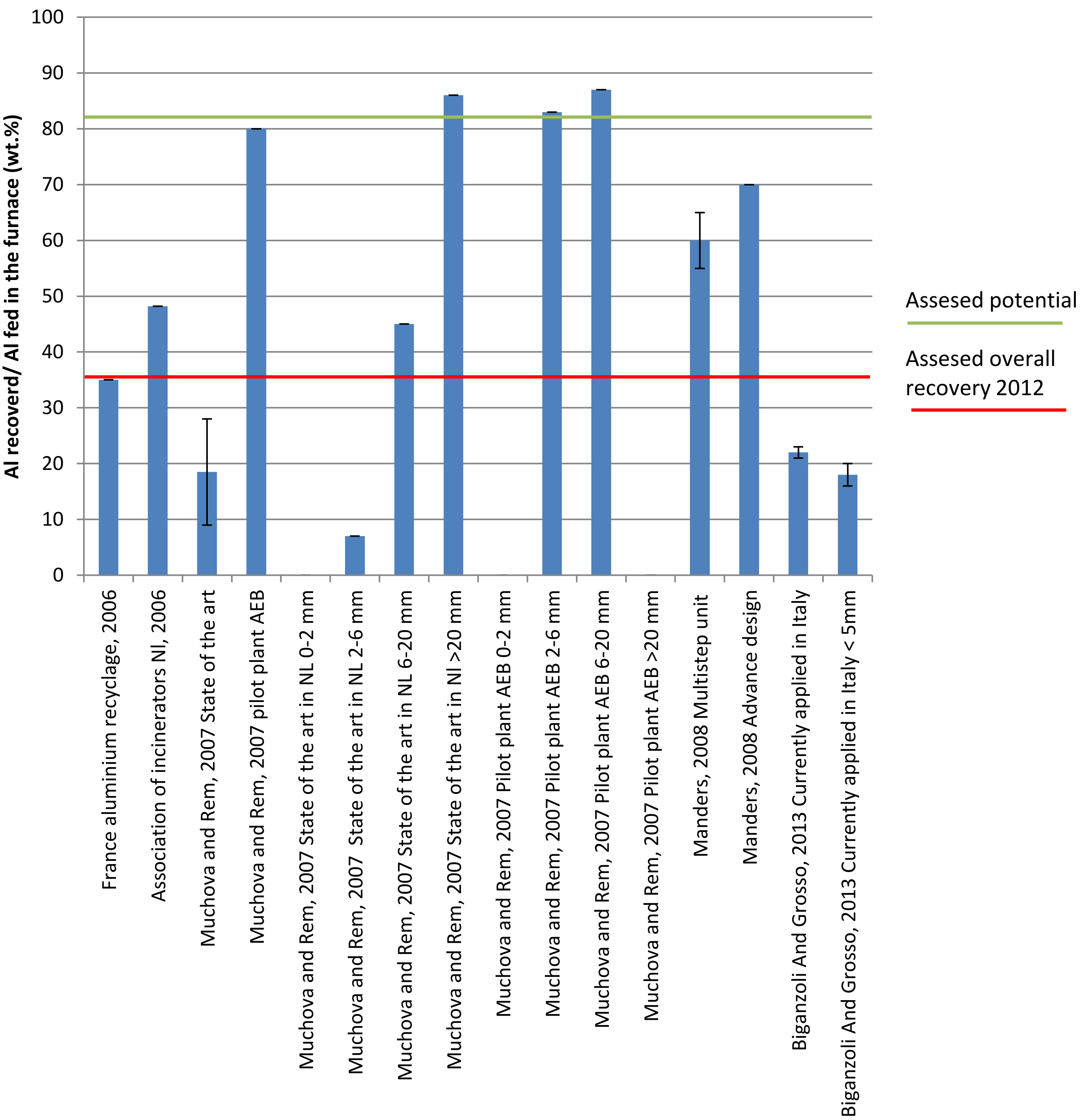
Annex II 1: overview of literature reports on aluminium recovery based on (Biganzoli, 2012) with some additions*

Reference		u.o.m.	Recovery rate
Magnus Project NL, 2003		% in mass (recovered Al/bottom ash)	1.77
Aluminium and Miljo DK, 2003	Kara >6 mm	% in mass (recovered Al/bottom ash)	0.36
	Vestforb > 6 mm	% in mass (recovered Al/bottom ash)	0.128
	Vejen > 6 mm	% in mass (recovered Al/bottom ash)	0.288
	Odense > 6 mm	% in mass (recovered Al/bottom ash)	0.352
Rem et al, 2004	AEB pilot plant	% in mass (recovered Al/bottom ash)	1.2
Dutch Waste Management Association NL, 2006		% in mass (recovered Al/bottom ash)	0.7-1.5
CiAl, 2006		% in mass (recovered Al/bottom ash)	0.49-1.17
Alu DK, 2006		% in mass (recovered Al/bottom ash)	0.65-0.78
Muchova et al, 2006	Pilot plant AEB	% in mass (recovered Al/bottom ash)	1.62
Muchoval and Rem, 2007		% in mass (recovered Al/bottom ash)	0.35-1.05
Astrup et Al, 2007		% in mass (recovered Al/bottom ash)	0.16-0.4
Barcellesi, 2008		% in mass (recovered Al/bottom ash)	0.8
Kok, 2011*	Pilot plant wet screening Boskalis HVC	% in mass (recovered Al/bottom ash)	0.48
Lamers, 2008		% in mass (recovered Al/bottom ash)	0.8
		% in mass (recovered Al/Al in the bottom ash	32
France aluminium recyclage,2006		% in mass (recovered Al/Al fed in the furnace)	35
Dutch Waste Management Association Nl,		% in mass (recovered Al/Al fed in	48.2

2006		the furnace)	
Muchova and Rem, 2007	State of the art	% in mass (recovered Al/Al fed in the furnace)	9-28
	Pilot plant AEB	% in mass (recovered Al/Al fed in the furnace)	80
	State of the art in NL 0-2 mm	% in mass (recovered Al/Al fed in the furnace)	0
	State of the art in NL 2-6 mm	% in mass (recovered Al/Al fed in the furnace)	7
	State of the art in NL 6-20 mm	% in mass (recovered Al/Al fed in the furnace)	45
	State of the art in Nl >20 mm	% in mass (recovered Al/Al fed in the furnace)	86
	Pilot plant AEB 0-2 mm	% in mass (recovered Al/Al fed in the furnace)	0
	Pilot plant AEB 2-6 mm	% in mass (recovered Al/Al fed in the furnace)	83
	Pilot plant AEB 6-20 mm	% in mass (recovered Al/Al fed in the furnace)	87
	Pilot plant >20 mm	% in mass (recovered Al/Al fed in the furnace)	n.d.
Manders, 2008	Multistep unit	% in mass (recovered Al/Al fed in the furnace)	55-65
	Advance design	% in mass (recovered Al/Al fed in the furnace)	70
Biganzoli And Grosso, 2013*	Currently applied in Italy	% in mass (recovered Al/Al fed in the furnace)	21-23
	Currently applied in Italy < 5mm	% in mass (recovered Al/Al fed in the furnace)	16-20
Pruvost, 2009	State of the art in France	% in mass (recovered Al/Al input to the bottom ash treatment plant)	65-70



Annex II 2: overview of the amount of aluminium recovered from bottom ash



Annex II 3: overview of the amount of aluminium recovered from bottom related to the amount of aluminium fed into the furnace

Annex III: Incineration of MSW and derivative product streams for 2012

	Waste incinerated	Bottom Ash (Raw)	Bottom Ash (processed)[65]	Ferro (Clean)[66,67]	Non-Ferro (Clean) [3]	RVS (Clean)[3]	Fly Ash[68]	Flue Gas Cleaning Salts	Gypsum	Others[69]
	Tonne	Tonne	Tonne	Tonne	Tonne	Tonne	Tonne	Tonne	Tonne	Tonne
AEB Amsterdam	1 407 844	336 123	298 051	19 834	2 820	895	17 754	16 783	2 161	786
ARN	294 060	84 761	52 634	5 464	1 099	156	4 205	4 133	1 246	548
AVR Duiven	383 589	104 290	105 300	5 166	1 008	221	4 427	0	0	3 048
AVR-AEC Rozenburg	1292 806	315 018	283 957	15 978	4 859	485	25 138	0	0	2 387
AVR-BEC Rozenburg	142 661	5 595	At AVT-AEC	At AVT-AEC	At AVT-AEC	At AVT-AEC	2 166	0	0	57
Atterro	673 802	221 330	188 190	13 184	2 406	227	5 248	7 802	0	0
Attero Moerdijk	915 192	268 917	251 582	13 723	2 886	261	15 408	0	0	10 355
Eon Delfzijl	316 318	87 407	60 000	1 800	219	0	16 577	690	0	0
HVC-AEC Alkmaar	632 067	168 025	212 894	16 113	2 633	558	6 921	5 611	0	2 606
HVC-BEC Alkmaar	185 088	0	At HVC-AEC	At HVC-AEC	At HVC-AEC	At HVC-AEC	5 076	3 345	0	0
HVC Dordrecht	301 049	71 601	At HVC-AEC	At HVC-AEC	At HVC-AEC	At HVC-AEC	2 699	0	0	193
REC Harlingen	227 733	45 332	31 494	2 785	957	68	4 927	5 270	0	0
SITA Roosendaal	330 676	76 077	68 408	4 540	1 170	116	1 845	7 184	0	0
Twence AEC Hengelo	604 407	149 535	143 055	11 734	2 136	-	6 781	9 469	0	2 014
Twence BEC Hengelo	159 272	10 000	At Twence AEC	At Twence AEC	At Twence AEC	At Twence AEC	2 151	1 707	0	810
HVC-SVI Dordrecht[70]	369 300	121	0	0	0	0	23 182	0	0	123
SNB-SVI Moerdijk[6]	432 717	1 964	0	0	0	0	36 953	1 860	0	619
Total AEC	**7 379 543**	**1 928 416**	**1 695 565**	**110 321**	**22 193**	**2 987**	**111 930**	**56 942**	**3 407**	**21 937**
Total BEC	**48 7021**	**15 595**	**At AEC**	**At AEC**	**At AEC**	**At AEC**	**9 393**	**5 052**	**0**	**867**
Total SVI	**802 017**	**2 085**	**0**	**0**	**0**	**0**	**60 135**	**1 860**	**0**	**742**

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[65] Not necessarily from the same year as produced BA

[66] At AVR Rozenburg this includes anchors (15 % Cu and 85 % Fe

[67] Metal values are corrected for impurities in some cases values are estimated

[68] Fly ash may contain absorbent

[69] This category contains all other products such as filter cake, sludge, boiler ash, active carbon etc.

[70] Dry content of sludge is SNB: 24 % and HVC: 22 %

	Waste incinerated	Estimated aluminium in waste (0.55%)	Non-Ferro (clean)	Estimated Aluminium recovered (2/3 from NF)	Recycling factor
	Tonne	Tonne	Tonne	Tonne	
AEB Amsterdam	1407844	7743	2820	1880	24%
ARN	294060	1617	1099	733	45%
AVR Duiven	383589	2110	1008	672	32%**
AVR-AEC Rozenburg	1292806	7110	4859	3239	46%*
Atterro	673802	3706	2406	1604	43%
Attero Moerdijk	915192	5034	2886	1924	38%
Eon Delfzijl	316318	1740	219	146	8%
HVC-AEC Alkmaar	632067	3476+1656	2633	1755	34%
HVC Dordrecht	301049	1656	At HVC-AEC		
REC Harlingen	227733	1253	957	638	51%*
SITA Roosendaal	330676	1819	1170	780	43%*
Twence AEC Hengelo	604407	3324	2136	1424	43%

*Applied ADR in 2012

**Applied ADR in Q4 of 2012

Annex IV: Data collection for the analysis of aluminium recovery from MSWI bottom ash

Annex IV 1: aluminium content of NF according to different sources

Source:	Aluminium content NF:	Comment
Fenix	62.70%	
Ffact	50%	Assumption, no measurement
AEB	40-45%	Without the ADR recovery, so actual value is higher. Value is in combination with bottom ash
Twence	68%	
Boskalis/HvC	61%	
Inashco	67%	

Annex IV 2: electricity use for different bottom ash treatment plants

Description:	Electricity use (kWh/tonne):	Source:
Fenix (Bottom ash treatment for HVC Alkmaar)	3.55	Royal Haskoning CO_2-footprint toepassing AVI-bodemas, 2009
Plant 1	2.2	Oudenhoven
Plant 2	2.8	Oudenhoven
Plant 3	5.8	Oudenhoven
AEB	3	Mijs
Plant	4	Grosso CEWEP
Heros	2.15	van Hoeve
Plant (innovative)	3.6	Ulrich Kohaupt
Plant (dry)	8	Muchova
Used in this analysis	**3.5**	

Annex V: Clean non-ferrous sorted by KGS in 2012

Bottom ash treated by Heros (tonne)	383 859
Bottom ash produced by AVR-AEC Rozenburg (tonne)	283 957
Bottom ash produced by by REC Harlingen (tonne)	31 494
Bottom ash produced by SITA Roosendaal (tonne)	68 408
Bottom ash produced by AVR Duiven (tonne)	105 300
AVR Duiven Q1-Q3 (tonne)	78 975
AVR Duiven Q4 (tonne)	26 325
Total treated by central bottom ash plant (tonne)	410 184
Bottom ash treated conventional	33%[71]
Bottom ash treated conventional (tonne)	215 703
Bottom ash treated by ADR	67%[72]
Bottom ash treated by ADR	273 456
NF recovered by ADR	0.90%
NF recovered by ADR (tonne)	2 461

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[71] Source: Inashco (2014)

Annex VI: Complete sensitivity analysis

	-50%	**-25%**	**0%**	**25%**	**50%**
Non-Ferrous metal recovered	12.6	18.9	25.2	31.5	37.8
CO_2 emission in recovery and recycling of aluminium (kg)	267 042 799	238 640 945	210 230 685	181 813 152	153 389 273
CO_2 emission in recovery and recycling of aluminium (ktonne)	267.0	238.6	210.2	181.8	153.4
	-10%	**-5%**	**0%**	**5%**	**10%**
CO_2 emissions primary aluminium production	6932.7	7317.85	7703	8088.15	8473.3
CO_2 emission in recovery and recycling of aluminium (kg)	188 959 955	199 635 798	210 230 685	220 987 484	231 663 327
CO_2 emission in recovery and recycling of aluminium (ktonne)	189.0	199.6	210.2	221.0	231.7
	-10%	**-5%**	**0%**	**5%**	**10%**
Natural gas use	630	665	700	735	770
CO_2 emission in recovery and recycling of aluminium (kg)	210 128 327	210 224 608	210 230 685	210 417 170	210 513 451
CO_2 emission in recovery and recycling of aluminium (ktonne)	210.1	210.2	210.2	210.4	210.5
	-20%	**-10%**	**0%**	**10%**	**20%**
Diesel use truck	0.032	0.036	0.04	0.044	0.048
CO_2 emission in recovery and recycling of aluminium (kg)	210 110 078	210 206 551	210 230 685	210 399 496	210 495 969
CO_2 emission in recovery and recycling of aluminium (ktonne)	210.1	210.2	210.2	210.4	210.5

	-50%	**-25%**	**0%**	**25%**	**50%**
Oxidation factor	7.50%	11.25%	15.00%	18.75%	22.50%
CO_2 emission in recovery and recycling of aluminium (kg)	213 894 245	212 107 567	210 230 685	208 534 211	206 747 532
CO_2 emission in recovery and recycling of aluminium (ktonne)	213.9	212.1	210.2	208.5	206.7
	-10%	**-5%**	**0%**	**5%**	**10%**
Aluminium in NF mixture	60.3%	63.7%	67.0%	70.4%	73.7%
CO_2 emission in recovery and recycling of aluminium (kg)	219 930 739	214 798 777	210 230 685	204 685 794	199 704 772
CO_2 emission in recovery and recycling of aluminium (ktonne)	219.9	214.8	210.2	204.7	199.7