Aluminium Mass Balance in Waste Incineration and Recovery Potential From the Bottom Ash: A Case Study

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Introduction

In recent years, aluminium scraps recovery from waste incineration bottom ash has become a common practice in integrated waste management scheme [1], fostered by the avoided problems of swelling and expansion that metals can cause when bottom ash is reused in concrete production or in road construction [2, 3] and by the environmental advantages connected to its recycling, especially in terms of savings of CO_{2eq} emission [4].

The scraps are separated from the ash stream through eddy current separators (ECS), whose average efficiency is about 1 % of the bottom ash mass [1]. However, some advanced technologies such as wet eddy current separators (WECS), Magnus ECS and backward operating ECS [5–7], included within advanced bottom ash treatment plants comprising several stages of sieving and crushing, can reach higher recovery rates by improving the selective separation of small non-ferrous metal particles below 2–5 mm [8].

Independently on the layout of the bottom ash treatment plant, it is important to remember that only the aluminium in the metallic form can be recycled. During the combustion process, the scraps contained in the waste undergo oxidation and volatilization processes that determine a loss of their recoverable mass from the bottom ash [9]. The thin scale of oxide that is formed on the surface of the scraps as a consequence of the reactions with the oxidizing compounds contained in the combustion flue gas, such as O_2, SO_2, HCl, as well as the molten salts which collect over the metal surface cannot be recycled and represent a loss from the point of view of material recovery. Such oxidation can be further enhanced when bottom ash is quenched in water after its discharge from the furnace grate. The strong thermal shock can break down the oxidation layer, facilitating a further

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degradation of the scraps. All these processes affect the recycling efficiency of the metal scraps.

The scraps separated from the bottom ash are melted in a furnace for the production of recycled secondary aluminium. The most common device used in the secondary aluminium industry is the rotary furnace, where aluminium scraps are melted under a layer of salt, which consists of a mixture of approximately 30 % KCl and 70 % NaCl, but can contain small amounts of CaF_2 [10]. This salt layer fulfils a variety of tasks: it enhances the heat transfer to the metal, it prevents its oxidation and takes up the contaminants, such as oxides, carbides and others contained in the scraps or produced by reactions during the melting process. In fact, the presence of aluminium oxide in the scraps promotes the formation of foams during the melting process because of its lower density compared to aluminium. These foams are removed with the salt but, along with them, part of the molten aluminium is inevitably lost. For this reason, aluminium lumps resulting from bottom ash treatment are fed in small percentages to the saline furnaces for the production of secondary aluminium, excluding the material that is too fine in order to avoid dramatic drops in terms of recovery yields.

The knowledge of the aluminium mass balance in a waste-to-energy plant and of its oxidation level is, therefore, essential to evaluate the potential of aluminium recovery from the bottom ash. However, even if several papers report the amount of aluminium scraps that can be separated from the bottom ash [11–14], only very few of them consider the oxidation processes that involve these scraps and report the amount of metallic Al actually recoverable and recyclable. Hu et al. [15] investigated the behaviour of selected aluminium packaging materials in the furnace of WTE plants at a laboratory scale. A similar investigation was performed by Biganzoli et al. [9] in full-scale WTE plants, allowing to estimate the amount of aluminium packaging materials potentially recoverable from the bottom ash. However, the authors did not find any publication that investigates the behaviour of the mixed aluminium in the residual waste and its recovery potential from the bottom ash. This aspect is very interesting since the residual waste contains not only aluminium packaging but also other aluminium items, such as pots and coffee pots [1]. In addition, waste composition differs from one place to another, and the characteristics of the aluminium in the residuals waste depend on the specific separated collection scheme that is implemented.

This paper investigates the behaviour of the mixed aluminium in the residual waste fed to incineration furnaces, by evaluating the partitioning of the total and metallic Al in the residues of full-scale WTE plants. The percentage of the aluminium in the waste that can be actually recycled from the bottom ash is evaluated,

providing a relevant and innovative information for the aluminium production industry.

Materials and Methods

Plants Description

The experimental tests were carried out in two incineration plants located in northern Italy that will be referred to as plant A and plant B.

Plant A consists of two treatment lines, with a throughput of about 6 and 9.5 tonnes per hour of waste. The feeding includes urban, urban-like non-hazardous waste and hospital waste (the latter accounting for about 8 % of the total waste feed). The plant is equipped with a forward-acting grate and a wet discharge system for the bottom ash, whose moisture content is equal to 22 % on average. The grate is divided into four sections whose movement can be regulated independently. The secondary air feeding is regulated to maintain the temperature above 850 °C for at least 2 s, and the oxygen concentration in the flue gas at around 6 %. A fraction of the clean flue gas (about 15 %) collected downstream the fabric filter is recirculated in the combustion chamber, in order to reduce NOx formation and to increase the steam production. The plant is equipped with a waste heat boiler for combined heat and power (CHP) production through a steam turbine. Flue gas treatment configuration is based on a dry-wet integrated process design and includes a dry stage for the removal of acid gases and micro-pollutants with the injection of sodium bicarbonate and activated carbon; a filtration stage with a fabric filter operating at 180 °C; a catalytic reactor with ammonia injection for the removal of NOx (SCR) and dioxins; and a wet scrubber with water and soda injection to complete the removal of the acid gases and the most volatile heavy metals such as mercury.

Plant B consists of two identical treatment lines, with a throughput of about 7.5 tonnes per hour of waste each. The typical feeding includes urban, urban-like non-hazardous waste, sewage sludge and hospital waste (the last two accounting for about 5 % of the total waste feed).

The furnaces are equipped with a backward-acting grate (supplied by Martin GmbH) divided into four sections, whose movement can be regulated independently. Primary air is fed from underneath the grate. At the end of the grate, the bottom ash falls down in a water bath, where it is quenched, and is then extracted with the "gondola" Martin device. The extraction system is designed to decrease the moisture content of bottom ash, thanks to its squeezing in the discharge slide; the final moisture content of bottom ash is in fact quite low, 13 % on average. The bottom ash is then discharged on a conveyor belt, where a magnet removes the big ferrous scraps.

The plant is equipped with a waste heat boiler for combined heat and power (CHP) production through a steam turbine. Flue gas configuration is based on a dry process design and includes a first injection of ammonia and of a sorbent (Depurcal MG®) in the combustion chamber to remove part of the NOx and acid gases; a high-dust catalytic reactor to complete the removal of NOx; an electrostatic precipitator (ESP); the injection of lime and activated carbon to complete the removal of the acid gases and of the micro-pollutants and a final stage of filtration with a fabric filter (FF).

The main characteristics of the two plants are reported in Tables 1 and 2, and the average waste composition is reported in Table 3.

Field Tests

Bottom and fly ash were sampled every 30 min for about 6–8 h per day for a total of 4 days in plant A and 3 days in plant B, in order to have a sufficient amount of samples representative of the standard operation of the plants. Bottom ash was sampled from the conveyor belt in a quantity of about 5–15 kg per sample. In plant A, all the fly ash (from the boiler and the filter) was sampled together, at its discharge in the big bags and collected in plastic pots of 1 l each. On the contrary, in plant B, boiler, ESP and FF ash were sampled separately from the redler transportation system, collecting the ash from the openings used for the maintenance.

Aluminium potentially present in the flue gas at the stack was voluntarily neglected as a previous research study focusing on the balance of trace elements showed that it is negligible [9].

Samples Analysis

Bottom and fly ash were analysed to evaluate their content of total and metallic Al, according to the procedure reported in Biganzoli et al. [9].

Prior to the analyses, the bottom ash was pre-treated according to the scheme reported in Fig. 1. It was first dried (step 1) and then screened at 0.8 mm (step 2). The choice of 0.8 mm as cut dimension is due to the recycling

Table 2 Incinerated waste and residues produced on average by the tested lines of plants A and B

Waste and residues	Plant A	Plant B	
MSW (t year^{-1})	37,119	34,456	
Urban-like waste (t year^{-1})		21,704	
Hospital waste (t year^{-1})	3,137	990	
Sludge (t year^{-1})	0	2,075	
Total waste (t year^{-1})	40,256	59,225	
Bottom ash (t year^{-1})	7,558	11,282	
Bottom ash (kg t$_{waste}^{-1}$)	187.3	190.5	
Fly ash (t year^{-1})	1,221	Boiler ash[a] (t year^{-1})	952
		Boiler ash (kg t$_{waste}^{-1}$)	16.1
		ESP ash[a] (t year^{-1})	476
		ESP ash (kg t$_{waste}^{-1}$)	8.0
Fly ash (kg t$_{waste}^{-1}$)	30.7	FF ash (t year^{-1})	1,228
		FF ash (kg t$_{waste}^{-1}$)	20.7

[a] The partitioning between Boiler ash and ESP ash is tentatively estimated by the plant operator

Table 1 Main operating parameters of the plants during the experimental campaigns (average values)

Average daily value	Plant A	Plant B
HCl raw gas[a] (mg m$_n^{-3}$)	1,066.25	457.00
CO raw gas (mg m$_n^{-3}$)	2.74	n.a.
SO$_2$ raw gas (mg m$_n^{-3}$)	56.39	n.a.
NOx raw gas (mg m$_n^{-3}$)	228.21	n.a.
Flue gas at the stack[b] (m$_n^3$ h^{-1})	44,255	35,456
O$_2$ combustion chamber (%v/v)	5.42	6.07
Grate temperature (°C)	1,011	n.a.
Combustion chamber temperature (°C)	828	866
Primary air (m^3 h^{-1})	20,509	21,329
Secondary air (m^3 h^{-1})	9,527	3,913
Flue gas recirculation (m^3 h^{-1})	4,397	866
Steam pressure (atm)	41.17	38.17
Steam temperature (°C)	400	391
Steam flow rate (t h^{-1})	25.59	22.76

[a] Dry gas at 11 % of O$_2$

[b] Dry gas

Table 3 Average composition of the residual waste incinerated in plants A and B

Waste composition (%)	Plant A	Plant B
Aluminium	0.73 ± 0.00	1.67 ± 1.08
Paper and paperboard	24.77 ± 4.31	31.68 ± 6.05
Plastic	23.22 ± 5.25	27.14 ± 6.66
Ferrous metal	2.13 ± 1.07	1.85 ± 1.59
Wood	1.16 ± 0.58	3.45 ± 2.91
Glass	1.45 ± 0.05	3.06 ± 2.09
Laminated	0.79 ± 1.40	n.a.
Organic fraction	16.41 ± 5.85	13.37 ± 9.29
Green waste	5.47 ± 8.66	Included in the organic fraction
Textile	4.35 ± 1.76	7.07 ± 4.58
Inert fraction	1.97 ± 1.26	0.83 ± 1.65
Fines	5.14 ± 1.58	5.37 ± 4.30
Other waste (nappies, leather, non-classifiable waste)	11.34 ± 3.48	3.11 ± 2.72
Hazardous waste	1.05 ± 0.34	0.49 ± 1.78
LHV (kJ kg^{-1})	15,391 ± 3,471	14,207 ± 3,194

capacity of aluminium secondary smelters. Particles bigger than 0.8 mm can generally be recycled, whereas those smaller than 0.8 mm cannot be recovered and determine a loss of material. Iron and inert scraps (step 3) and non-ferrous lumps (step 4) were manually sorted out. The fraction above 0.8 mm was grinded in a grindstone (step 5) in order to make its laboratory analysis possible and afterwards it was further screened at 0.8 mm (step 6). In this way, it was possible to isolate the coarse fraction (above 0.8 mm) rich of metals which, unlike the inert material, are not crushed in the grindstone but just flattened.

The two inert fractions below 0.8 mm (before and after the grinding) were analysed separately. In these fractions, aluminium is present in low amount and the content of total aluminium was evaluated with X-ray fluorescence spectroscopy (XRF), while that of metallic aluminium was detected using caustic soda attack followed by the

measurement of the volume of the produced hydrogen. The analysis of metallic aluminium with the soda attack method is quite common and reported in other papers [9, 15, 16]. The chemical reaction that controls the hydrogen production is given in Eq. 1:

$$2Al + 2OH^- + 2H_2 \rightarrow 2AlO_2^- + 3H_2 \tag{1}$$
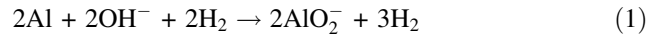
The fraction above 0.8 mm resulting from the second screening underwent an iron sorting with magnet (step 8) and it was then melted with salt in the crucible (step 9) together with the aluminium lumps manually sorted in the previous steps. The salt dross was analysed with the same procedure as for the inert fraction of the bottom ash, whereas the recoverable metal ingot was analysed by an optic emission spectrometer (OES or quantometer), in order to evaluate its content of Al (all considered metallic) (step 10). During the last sampling day in plant A and during the tests in plant B, the fraction above 0.8 mm resulting from the second screening, after iron sorting with the magnet, was screened again with a 5-mm-mesh screen (step 11). The fraction above 5 mm and the aluminium lumps manually sorted, consisting almost entirely of aluminium and other non-ferrous metals and representing non-ferrous metals that can be separated with a traditional ECS, were melted together to obtain the metal ingot. The fraction between 0.8 and 5 mm, representing the material that can be recovered only with advanced ECS, such as high-frequency ECS, wet backward ECS and Magnus separator specifically calibrated, was melted separately and its dross analysed with soda attack and XRF.

Fly ash samples were directly analysed with soda attack and XRF in order to determine their content of metallic and total aluminium, respectively (step 7).

The main difference between the analyses of samples from plants A and B regards the laboratory device for the measurement of metallic aluminium content with the "soda attack" method, which was partially modified by substituting the mercury column used for the pressure reading with a digital sensor for gas velocity and flow meter measurement (Flowtest ST by Tecora). This allowed for a better precision, and a consequent reduction in the standard deviation associated with the metallic Al measurement, which decreased from 0–72 % [9] to 5–25 % of the average values.

Results

Aluminium Mass Balance

Total aluminium partitioning in the residues of the incineration process during standard operating conditions is reported in Fig. 2.
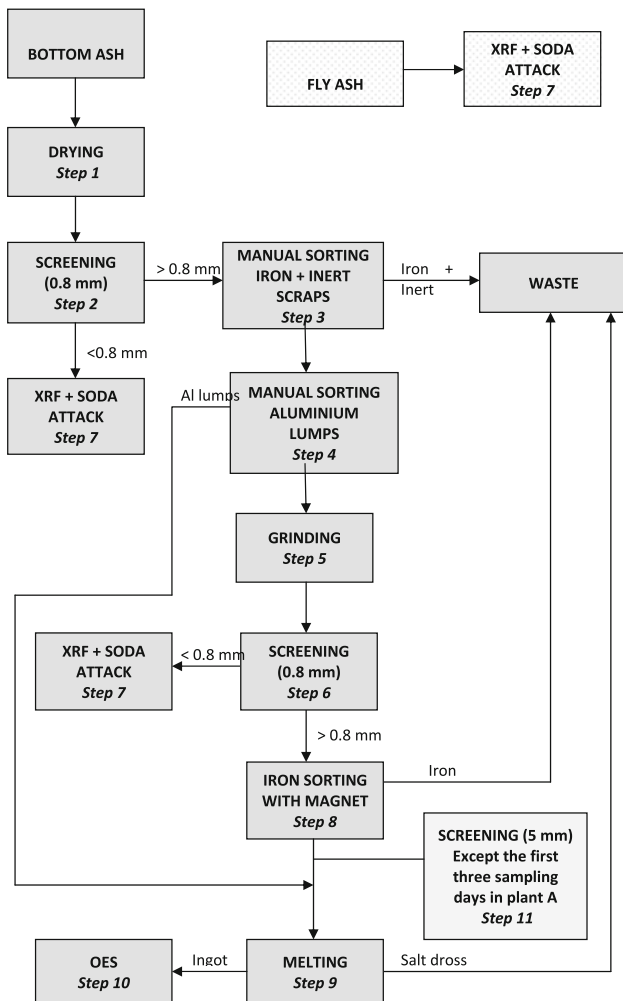

Fig. 1 Samples treatment and analysis. *XRF* stays for X-ray fluorescence spectroscopy, *OES* for optic emission spectrometer. The *Soda attack* method was used for the evaluation of the metallic Al content in the ash
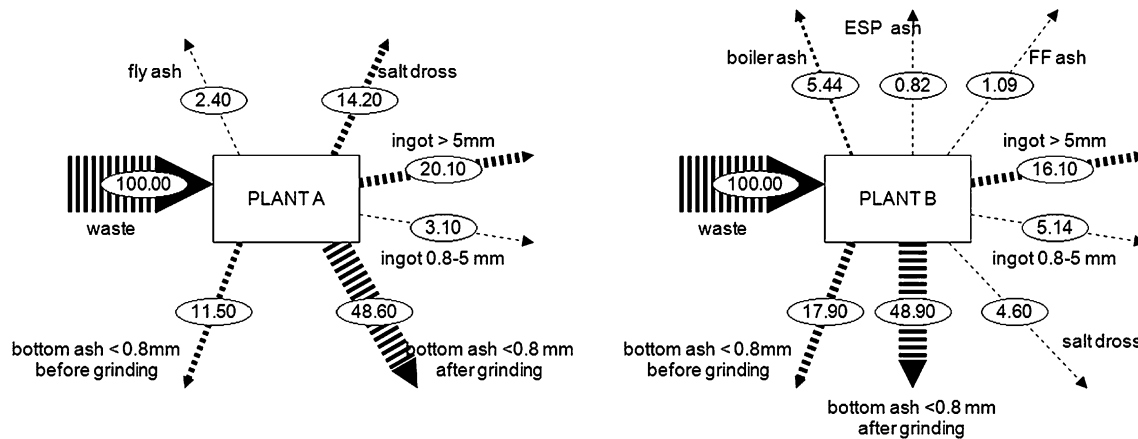
Fig. 2 Total Al mass balance in plants A and plant B. Aluminium concentration in the flue gas is not included

The ingots fraction is representative of the metal actually recyclable from the bottom ash. In fact, since it is obtained from the melting process, it includes also the efficiency of the recycling process. On the contrary, the aluminium in the other residues (fly ash, bottom ash below 0.8 mm before and after grinding) represents a loss, because it cannot be recovered neither recycled in the secondary aluminium smelter. In both fine fractions, aluminium metal fragments are extremely small in size and their recovery is virtually impossible using the current ECS technology.

The partitioning of aluminium in the residues of the combustion process results quite similar for the two plants. On average, about 61–67 % of the aluminium concentrates in the fine fraction of the bottom ash and cannot thus be recovered with the actual technologies. Only 21–23 % can be recovered from the bottom ash and recycled as ingots. Out of this amount, 13–24 % comes from the bottom ash fraction included between 0.8 and 5 mm and 76–87 % from the fraction bigger than 5 mm. This means that, even if most of the aluminium scraps are recoverable through standard eddy current technologies, a non-negligible amount of aluminium can be recovered only in advanced treatment plants, equipped with a grinding stage and advanced eddy current separators.

The aluminium that during the combustion process concentrates in the fly ash results relatively low compared to the bottom ash fraction and included between 2.5 and 7 %, almost completely found in the boiler ash.

For what concerns the salt dross, it must be said that the melting process performed during the experimentation was characterized by a lower efficiency compared to the one taking place in the full-scale smelter. In fact, the non-ferrous metals recovered from the bottom ash were melted together, without a previous separation of the Al lumps from the other non-ferrous scraps. As this non-ferrous mix had a lower content of Al compared to the material usually treated in a smelter, the efficiency of the melting process performed during our investigation was lower than the true recycling efficiency of a full-scale smelter, where such low-quality materials are usually diluted in a cleaner aluminium charge. When assuming the metallic Al trapped in the salt dross as potentially recoverable (Eq. 2), the recovery efficiency of aluminium from the bottom ash increases to about 28–38 %:

$$\text{Al recovery efficiency} = (\text{Al in the ingot fractions} \\ + \text{ metallic Al in the salt dross})/ \\ \Sigma \text{ total Al in all the residues}$$

By comparing the percentage of aluminium potentially recoverable from the bottom ash during standard operation with that found in a similar research devoted to selected packaging materials (cans, trays and a mix of aluminium foil and poly-laminated foil) [9], we notice that the mixed residual waste behaves similar to the foils. This suggests that most of the aluminium in the residual waste consists of flexible packaging, like aluminium foil and poly-laminated foil. In fact, while the separated collection of cans and spray cans is well established and achieves a good efficiency, that of the flexible packaging is less widespread. Most of those materials are in fact used while cooking and, being contaminated by food residues, are not collected at the source but disposed together with the residual waste.

At this point, a clarification must be done: the results previously illustrated in Fig. 2 refer to two specific contexts of waste management. The amount of aluminium potentially recoverable from the bottom ash depends on the characteristics of the aluminium scraps (e.g. the percentage of flexible and rigid packaging) in the waste fed to furnace, as reported in Biganzoli et al. [9]. This means that different waste management systems, with a different organization and efficiency of the separated collection, will lead to a different recovery potential of Al from the bottom ash.

These results also challenge the values reported in the literature for advanced bottom ash treatment technologies. Some experiments carried out in Northern Europe, especially in the Netherlands, showed an aluminium recovery rate from the bottom ash much higher (up to 60–70 %) than the one resulted from the present investigation [11, 15, 17]. However, it is difficult to compare values from different researches, since the testing protocols are not always fully explained or comparable. In addition, information about the source separated collection of the aluminium packaging, and the average composition of the waste fed to incineration plants in the Netherlands was not found by the author. Thus, the interpretation of the different results is rather complex.

Aluminium Oxidation and Energy Recovery

Less than 50 % of the aluminium was found on average in the residues in the metallic form, as reported in Table 4. The plant design has an influence on the observed data. Plant A, which is equipped with a forward-acting rate, shows a higher percentage of metallic Al compared to plant B, equipped with a backward-acting grate. Furthermore, the residence time of the waste on the grate and in the bottom ash extraction turned out to be longer in plant B (9–10 h in plant B and 4–6 h in plant A), which means that the aluminium scraps are exposed for a longer time to high temperature oxidation processes.

Even if most of the aluminium is present in its oxidized form and thus cannot be recovered as a material, it contributes to the energy developed during the combustion process. In fact, it is known that at combustion temperatures above 850 °C, the complete oxidation of 1 kg Al into Al_2O_3 releases 31 MJ of energy, evaluated considering the standard molar enthalpy of formation of Al_2O_3, equal to 1,676 kJ/mol [18]. The energy potentially recoverable from aluminium oxidation in the waste is reported in Table 5. It must be specified that all of the oxidized aluminium has been assumed in the form of Al_2O_3, thus resulting in a specific energy release equal to 31 MJ/kg. This is not necessarily true because aluminium in the 3+ oxidation state might be present in other mineral phases (such as ettringite, zeolites or other alumino-calcium hydrate compounds), resulting in different specific energy releases. Therefore, the results of the calculation must be considered as rough estimates of the maximum amount of energy that can be released by Al oxidation processes.

On average, aluminium contribution to the energy released by the waste during the combustion process resulted equal to 1 %, almost proportional to its presence in the waste.

Other Non-ferrous Metals

Table 6 shows the average content of the most important elements in the ingots obtained from the melting process in the crucible. The results are reported separately for the tests carried out in plant A (where all the non-ferrous metals

Table 4 Average metallic Al content in the incineration residues (values expressed as percentage of metallic Al on total Al)

Residues	Plant A	Plant B
Boiler ash	85.9	37.9
ESP ash		47.7
FF ash		76.7
Bottom ash fraction <0.8 mm before grinding	26.6	12.0
Bottom ash fraction <0.8 mm after grinding	24.8	17.9
Ingots 0.8–5 mm	100.0	100.0
Ingots >5 mm		100.0
Dross salt	40.6	43.0
Average	46.2	37.4

Table 6 Average contents of other elements in the ingots from the melting process

	Cu (%)	Zn (%)	Si (%)	Pb (%)	Mn (%)	Mg (%)	Fe (%)	Al (%)
Plant A								
Total ingot								
Average	5.13	2.66	1.63	0.45	0.38	0.04	1.38	87.72
SD	4.08	1.56	0.92	0.27	0.11	0.03	0.43	5.21
Plant B								
Ingot (0.8–5 mm)								
Average	11.97	6.24	1.08	0.67	0.50	0.02	1.82	73.59
SD	3.82	1.71	0.33	0.40	0.10	0.01	0.88	7.60
Ingot (>5 mm)								
Average	5.01	5.33	1.50	0.56	0.27	0.07	0.76	85.14
SD	3.14	4.14	1.52	0.32	0.06	0.06	0.36	7.38

Table 5 Potential for energy recovery from the oxidation of aluminium scraps in the residual waste

	Oxidized Al (kg/tURW)	Energy release from Al (MJ/tURW)	LHV waste (MJ/t)	Energy contribution of Al (%)
Plant A	5.71	177.12	15,391	1.15
Plant B	4.62	143.25	14,207	1.01

lamps were melted together with the exception of the last sampling day) and in plant B (where the melting process was performed separately for the fractions <5 and >5 mm).

As a general indication, the highest content of metals other than aluminium was found for Cu and Zn, in decreasing order. On average, the ingots recovered from bottom ash of plant B are richer of other non-ferrous metals compared to those of plant A.

For what concerns plant B, almost all the metal content in the ingots obtained from the melting of the 0.8–5 mm sub-fraction are significantly higher than the corresponding values in the sub-fraction above 5 mm. The reason mainly lies in the generally higher concentrations of heavy metals that concentrate in the bottom ash fraction below 2 mm, as reported by Hu et al. [19]. In fact, while Al lumps usually concentrate in the bottom ash fraction above 6 mm, Cu, Zn and Pb scraps concentrate in the fraction smaller than 2 mm [19]. These metals mainly come from the electronic equipments incorrectly thrown away with the unsorted waste and they are characterized by a very small size compared to the Al packaging and items.

Conclusions

The experimentation carried out in two incineration plants located in northern Italy showed that about 21–23 % of the Al fed to the furnace with the residual waste can be recovered from the bottom ash as ingot. Out of this amount, 76–87 % is found in the bottom ash fraction above 5 mm and thus can be recovered with standard ECS. The remaining Al concentrates in the fine fractions of the bottom ash (60–67 %) or in the fly ash (2.5–7 %), and then cannot be recovered with the current technologies. Those values suggest that most of the Al in the residual waste consists of flexible packaging materials, like the aluminium foil and the poly-laminated foil, whose average recovery from the bottom ash amounts to about 27 %, as found in previous research [9].

The percentage of recoverable Al can potentially increase up to 28–38 %, depending on the efficiency of the recycling process. During the tests, in fact, all the non-ferrous metals collected from the ash were melted together, resulting in a very modest recycling efficiency. Among the other non-ferrous metals, the principal constituents are Cu and Zn, which mainly concentrate in the small lumps below 5 mm.

On average, about 54–63 % of the aluminium is oxidized during the combustion process. This Al represents a loss from the material recovery point of view; however, it contributes to about 1 % of the thermal energy released in the combustion chamber.

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