

Optimizing Non-Ferrous Metal Value from MSWI Bottom Ashes

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ABSTRACT

The bottom ashes resulted annually from the incineration of municipal solid waste in Europe contain about 400,000 tonnes of metallic aluminium and 200,000 tonnes of heavy non-ferrous metals, such as copper and zinc. Efficient recovery of this non-ferrous metal resource requires state-of-the-art separation technologies and a continuous feedback of laboratory analyses of the metal products and the depleted bottom ash to the operators of the bottom ash treatment plants. A methodology is presented for the optimization of the production of non-ferrous metal value from Municipal Solid Waste Incinerator bottom ash. Results for an incineration plant in the Netherlands show that efficient recycling can have a significant impact on value recovery as well as on non-ferrous metal recycling rates, producing up to 8% more revenue and 25% more metals from the ash.

Keywords: *Urban Mining, Solid Waste, MSWI Bottom Ash, Non-Ferrous Metals*

1. Introduction and Methods

The Municipal Solid Waste Incinerators (MSWI's) of Europe produce a vast stream of some 20 million tonnes of bottom ashes, annually [1]. The ashes contain, next to ferrous metals, significant amounts of non-ferrous metals like aluminium, copper, zinc and lead, ranging in particle size from over 100 mm down to less than 1 mm [2,3]. If the entire particle size range of the metals is taken into account, MSWI bottom ash may contain up to 10% of the copper and aluminium consumption on a per capita basis. Recovering non-ferrous metals from the ashes is therefore both a strategic asset [4] and an important step towards a sustainable use of resources. In view of the already advanced recycling of non-ferrous metals in European societies, it is perhaps even the largest single contribution yet to make.

An important economic drive for a more efficient recycling of bottom ash is the revenue of the metals. From 2002 to 2006, the LME price of copper increased from €1500 to €6000 per metric tonne. The worldwide economic crisis caused a steep price drop (to €2000/mt in Dec 2008) as a result of a decrease in demand. However, by May 2010 the price level had risen again to €6000/mt. Assuming average non-ferrous scrap prices over the past five years, a well-run bottom ash processing plant with an annual capacity of 100,000 tonnes creates a non-ferrous

scrap value of about 1.5 million Euro, which is sufficient to cover the cost (typically between 8 and 14 Euro/tonne) of the entire treatment that is necessary to convert the ash into a granular road filler. A positive externality of the production of secondary non-ferrous metals from bottom ash is a reduction of metal price fluctuations, as a result of the positive correlation between household waste volumes and the economy. From the viewpoint of ecology, comparative life cycle analyses for various bottom ash processing options show that the avoided environmental impact of the metallurgy of primary non-ferrous metal production and the reduced leaching potential of copper, zinc and lead from the ash more than outweighs the impacts of the treatment processes on the ash [5].

Despite the strategic, environmental and economic benefits of a proper recycling of MSWI bottom ashes, more than half of the non-ferrous metal in the European ash is presently lost to land fills and roads. If the ash is recycled at all, processing plants typically recover about one third of the total non-ferrous metals content. One reason for this disappointing performance is the complexity of the mechanical recovery of metals from the ash, which involves the optimization of several interconnected process variables. Bottom ash is nearly always quenched as it leaves the incinerator, resulting in a moist material that is difficult to process. The processability of the ash can be improved by optimizing the incineration

process to achieve a low organic content (often presented in terms of the LOI), and indirectly by a low moisture of the ash. An alternative is to compress the ash after taking it from the quench. Aging the ash for several weeks is very common, and has a beneficial effect on the processability, but tests at a large Dutch processor showed that aging of the ash for 10 weeks reduced the recoverable content of metallic aluminium by more than 6 kg/tonne of ash [6]. Other important parameters for the recovery are the type, number and the settings of the eddy current separators (ECS), which concentrate the non-ferrous metals from the ash.

Whichever process parameters are considered, a necessary first step for optimizing non-ferrous metals recovery is to implement a monitoring scheme involving quick and consistent analyses of the two products, *i.e.*, the non-ferrous concentrate and the metal-depleted ash, of the ECS. Reliable analysis results will allow the operator of the mechanical separation to optimize the process towards maximum non-ferrous value recovery. The aim of the present study is to develop a methodology that guarantees a consistent, reproducible value estimate that links directly to the post-processing of the metals by sink-floaters and smelters.

2. Analysis Methodology

Figure 1 presents the analysis scheme that was employed for measuring non-ferrous metal concentrations in this study. The scheme aims for reproducibility and efficiency. It is assumed that the two product streams of the ECS, the non-ferrous concentrate and the depleted ash, are sampled by combining a number of small samples taken at regular intervals from the downstream conveyors so as to produce samples that are representative for a certain period in time. Drying the product samples before the analysis is not essential. Wet screening will avoid the time-consuming drying step, but it will also complicate the subsequent handling of the -2 mm fraction, and the splitting and magnetic separation of the material. If the analysis is done on a regular basis, a tumble dryer may be used instead of the laboratory oven which was used in this study, to speed up the drying process. A tumble dryer may break some fragile aluminium particles into finer parts. However, the sink-floater is likely to pay for the aluminium on the basis of metal recovery after removing surface oxides, and this latter process is a much rougher treatment than tumbling.

The aluminium alloys (Al) and the heavy non-ferrous alloys (HNF) are the most relevant groups of non-ferrous metals [7-9] in terms of bottom ash scrap value. From the analysis point of view, it is relatively easy to determine also the non-magnetic stainless steel (SS) fraction next to the Al fraction and the HNF fraction. Since the alloy ra-

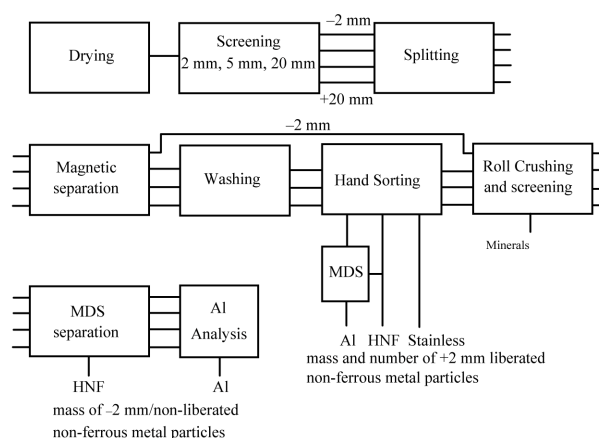


Figure 1. Full analysis scheme for the non-ferrous concentrate and the metal-depleted ash product of the ECS section. HNF indicates the heavy non-ferrous alloys, mainly copper alloys.

tios within the Al fraction and in the HNF fraction are fairly constant for a particular size fraction and a given bottom ash stream, and since further analysis to determine the element composition is both time-consuming and expensive, it was decided to limit the analysis to these three classes of alloys. The classification of the samples in terms of screen size was based on the fact that many sink-floaters have a problem with material smaller than 5 mm and that this size is also the lower limit to which conventional dry bottom ash processors are able to recover non-ferrous metals. Typically, dry treatment recovery rates of non-ferrous metals drop from almost 100% for particles larger than 20 mm to virtually zero at some lower particle size between 5 mm and 12 mm, depending on the screening steps and the ECS technology of the process. Wet processes [10,11] and the Advanced Dry Recovery process [6] recover aluminium and heavy non-ferrous particles down to 2 mm. The samples were therefore screened at 2 mm, 5 mm and 20 mm.

For efficiency, all size fractions were split after screening so as to balance the sampling errors of the downstream analyses. In this way, none of the samples analysed was larger than necessary to achieve the target accuracy for the total non-ferrous mass balance. Sampling errors were estimated by Gy's formula [12], which reduces to a particularly simple expression for not too high concentrations of materials in a (narrow) size fraction of a sample: if some material represents less than 20% of the particles in a size fraction and N is the number of particles of that material found in a sample of the size fraction, the relative sampling error in the concentration of the material is approximately $100\%/\sqrt{N}$. In other words, if x [kg/kg] is the measured concentration of some alloy in a size fraction, the absolute error in the concen-

tration is about x/\sqrt{N} . It was found that a sample size of 25 kg for the non-ferrous concentrate and a sample size of 100 kg for the non-ferrous depleted ash correspond to relative errors in the aluminium and heavy non-ferrous mass balances of around 3% and 5% respectively. According to Gy's formula, four times bigger (smaller) samples will result in a factor of two smaller (larger) sampling errors. The -2 mm, 2 - 5 mm and 5 - 20 mm fractions of the samples were split a number of times prior to the metal analysis. If the analysis error of some split sample turned out to compromise the accuracy of the final mass balance, up to four times more material of that size fraction was analysed (see **Table 1**). The amount of 0 - 2 mm non-ferrous concentrate was too small to be significant for the bottom ash processing site that was reviewed in this study.

Magnetic steel particles can be separated either by a rotary drum magnet or by passing a magnet over a monolayer of the material on a flat surface. If a hand-held magnet is used, the surface of the magnet should be cleaned regularly and the height of the magnet above the surface should be carefully defined to guarantee reproducibility of the results. As the magnet closes in on the sample, the increasing intensity of the magnetic field/magnetic field gradient will first lift the elongated and flat steel parts before lifting more compact steel parts. Further increase of the magnetic intensity will also attract magnetic slag, magnetic HNF alloys and finally aluminium particles in which a small ferrous piece was introduced during the molten phase in the incineration process. Magnetic HNF alloys represent up to 10% of the HNF alloy fraction and up to 20% of the aluminium pieces may be contaminated with a ferrous inclusion. Ferrous-contaminated aluminium and magnetic HNF particles can be separated by the ECS, so they should not be removed into the ferrous fraction during analysis. The results in this paper were obtained with a rotary drum magnet, which was always run at the same high belt speed.

After removal of the magnetic particles, size fractions larger than 2 mm were washed with water (L/S about 1) in a rotating vessel for 15 minutes and the fines were screened off. Then, the three alloy groups were separated

Table 1. Parts of the size fractions analysed for non-ferrous metals.

Size fraction mm	Part of size fraction analysed	
	Non-ferrous concentrate	Depleted ash
0 - 2	-	1/256 - 1/64
2 - 5	1/2 - all	1/64 - 1/8
5 - 20	1/4 - all	1/8 - 1/2
+20	all	all

from each other and from the glass, stone and slag, by hand sorting. Hand sorting of a sized and split sample is a relatively fast procedure, but experience shows that part of the HNF fraction tends to be recognised by the hand sorter as aluminium. In order to get consistent results, the hand-sorted aluminium fraction must be cleaned from HNF particles by sorting on density.

The most straightforward option for sorting the hand sorted aluminium on density is to sink-float the mixtures in a solution of Sodium Polytungstate of 2900 - 3000 kg/m³. The main disadvantage of this option is the large amount of work to recover the liquid from the products, which is necessary because of the high cost of this type of heavy liquid. Sodium Polytungstate also turns blue after extended contact with aluminium but this is reversible by adding peroxide. A cheaper alternative is Magnetic Density Separation (MDS, see **Figure 2**). The basic principle of MDS is to use a diluted magnetic liquid as the separation medium. In the absence of a magnetic field these liquids have a material density ρ which is comparable to that of water. But in a gradient magnetic field, the force on a volume of the liquid is the sum of the gravity and the magnetic force. The resulting apparent density varies exponentially with the vertical coordinate z :

$$\rho_{\text{apparent}} = \rho + \frac{\pi M B_0}{g p} e^{-\pi z/p} \quad (1)$$

Here, M is the magnetization of the magnetic liquid, B_0 is the magnetic induction at the surface of the magnet ($z = 0$) and p is the pole size. An MDS separator segregates the feed into stratified layers of different materials, so that each material floating at a specific distance above the magnet according to its density and the given formula. The present experiments were done with MDS using a five times diluted magnetic liquid from Ferrotec (see **Figures 2** and **3**). This liquid is so cheap that it is not necessary to recover it from the sorted products. A disadvantage of MDS is that aluminium particles with a significant ferrous inclusion may end up in the heavy fraction.

A small part of the non-ferrous metal content (typically 10%) is bound to or enclosed in slag particles. Such particles are usually not recovered by the ECS into the non-ferrous concentrate. The amount of non-liberated non-ferrous metals can be assessed by crushing the mineral fractions after hand sorting. A roll crusher tends to increase the screen size of the metal particles while it breaks the minerals to a size smaller than the distance between the rolls. After crushing, the Al and HNF can be concentrated by screening the crushed material at 2 mm to facilitate the hand sorting of the metals from the rest. Plastics are removed from the oversize by floating in



Figure 2. Equipment for MDS separation of aluminium (floating) from heavy non-ferrous metals (sunk and collected at bottom of the gutter).

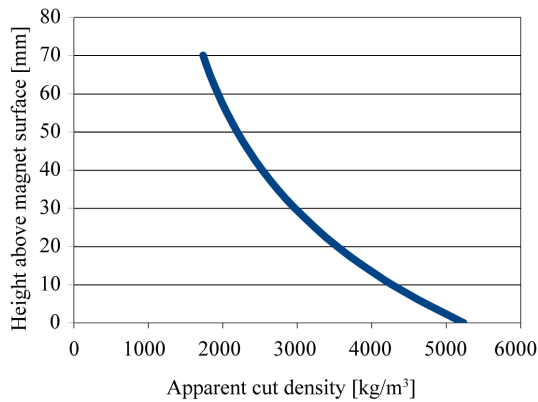


Figure 3. Apparent density ρ_{apparent} of the magnetic Ferrotec liquid on the magnet used for the density separations. The data are for $M = 2600 \text{ A/m}$, $\rho = 1070 \text{ kg/m}^3$, $B_0 = 0.6 \text{ T}$ and $p = 0.12 \text{ m}$. For these settings, copper is sinking and aluminium is floating at about 35 mm above the surface of the magnet.

water. Finally, the resulting non-ferrous mixture is separated into an Al fraction and a HNF fraction by density sorting. The original -2 mm fraction cannot be hand sorted because of its small particle size. Therefore, this fraction is separated only for HNF by density separation and the metallic aluminium content is established chemically by measuring the amount of hydrogen that is produced when the material is immersed in a concentrated sodium hydroxide solution (Figure 4).

3. Online Analysis

The purpose of the standard analysis described above is to generate data for estimating the price of the non-ferrous concentrate and for the optimization of the value recovery. An additional online analysis procedure was developed to be able to give a quick feedback on the separa-

tion performance within hours after sampling, allowing the operator to respond to fluctuations of the input. On-line analysis can replace most of the standard analyses, but now and then, a standard analysis has to be performed to be able to translate the results to absolute numbers. The online analysis procedure is presented schematically in Figure 5. The difference with the standard analysis is that the samples are not washed or hand sorted before crushing. The result is the total non-ferrous content, combining liberated and non-liberated pieces. Since crushing is a more intensive process than washing, more metal fines are produced by this procedure and the total non-ferrous content tends to be slightly less (10% - 13%, on average) than with the standard analysis. Instead of analysing all fractions, typically only the 2 - 5 mm and/or the 5 - 20 mm fractions will be analysed, because these are the primary focus of on-line optimization.

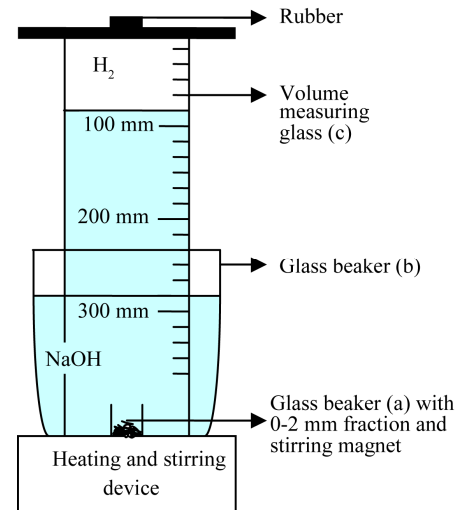


Figure 4. Laboratory setup for measuring the metallic aluminium content of 0 - 2 mm bottom ash fractions.

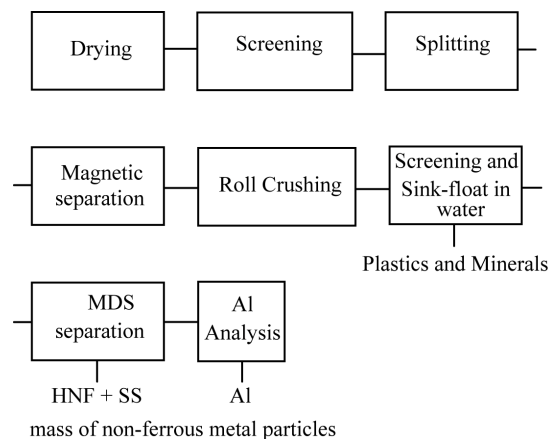


Figure 5. Online analysis procedure. HNF + SS indicates the combined heavy non-ferrous and stainless steel alloys.

4. Results and Discussion

Table 2 shows results of a standard analysis for a sample of the metal-depleted ash for a conventional dry treatment process in the Netherlands. Next to the concentrations of Al, HNF and SS, also the error estimates computed by Gy's formula are shown, to highlight the balance of contributions to the error in the overall non-ferrous metal concentrations by the individual size fractions.

The data of **Figure 6** represent averages of six analyses performed over a three-month period. It is clear that the recovery of aluminium and heavy non-ferrous alloys drops to zero halfway the 5 - 20 mm fraction, which is typical for conventional dry processes. Most ECS can recover flat stainless steel particles starting from about 20 mm, and this is confirmed by the data. The overall recoveries are about 50% for aluminium and 36% for the heavy non-ferrous alloys. **Figure 7** shows the effect of the cut-point of the ECS in the grade-recovery curve for aluminium. By changing the splitter position or the belt speed of the ECS, the recovery of aluminium into the non-ferrous concentrate can be increased at the expense of recovering relatively more slag (mineral). The data points show that although these settings are not the only factor determining the aluminium recovery, they are nevertheless a major one. The line drawn through the data was made by connecting the point of zero recovery and 100% aluminium grade with the point of 100% recovery of the ECS input and the input aluminium grade. These two extreme points can be realised by moving the splitter of the ECS so as to recover either all or none of the input material into the non-ferrous concentrate.

To optimize value recovery, an estimator is needed for the price of the non-ferrous concentrate. Sink-floaters will typically offer prices for MSWI non-ferrous scrap based on formulas that include the costs of sink-floating, smelting and the LME prices for the pure metals. A simple formula for the revenue of scrap in Euro/tonne is given by Equation (2):

$$\text{Revenue} = (100\% - F_S)$$

$$\cdot \left\{ (R_{Al} \text{LME}_{Al} - F_{Al}) \text{Al}\% + (\text{LME}_{Cu} - F_{Cu}) \text{Cu}\% \right\} \\ - L \text{Slag}\% - F_{SF}$$

F_S Sales fee

R_{Al} Recovery of aluminium from the smelt

F_{Al} Aluminum smelter fee

F_{Cu} Copper smelter fee

L Land fill fee

F_{SF} Sink-float fee

LME_{Al} LME price of Aluminium

LME_{Cu} LME price of Copper

(2)

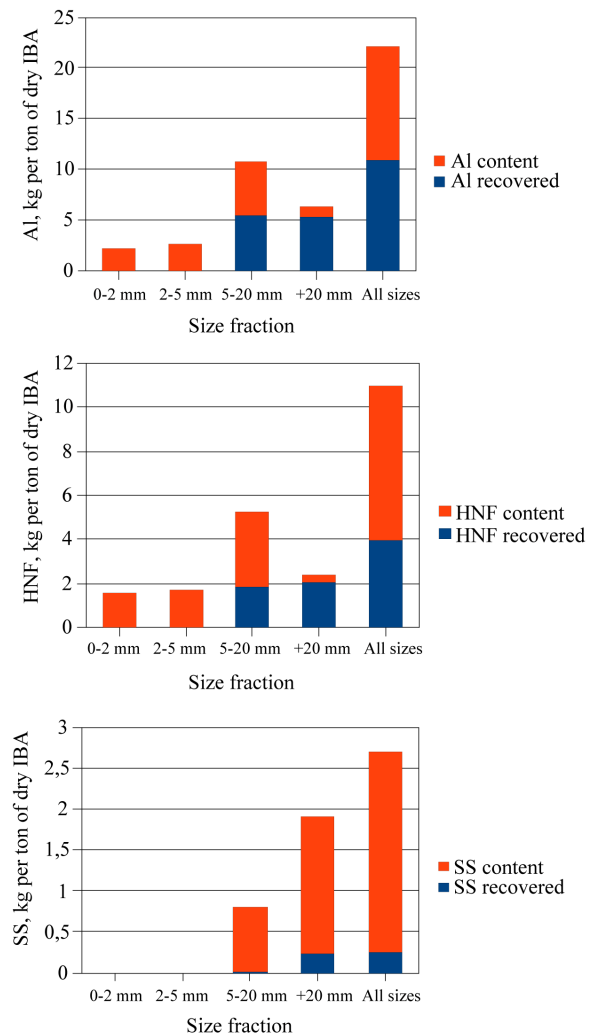


Figure 6. Average ECS input metal contents and recoveries of aluminium (Al, top), heavy non-ferrous (HNF, middle) and stainless steel (SS, bottom) for a Dutch conventional dry process in terms of kg per tonne of dry ECS input. The results have been averaged over six analyses performed in a period of three months.

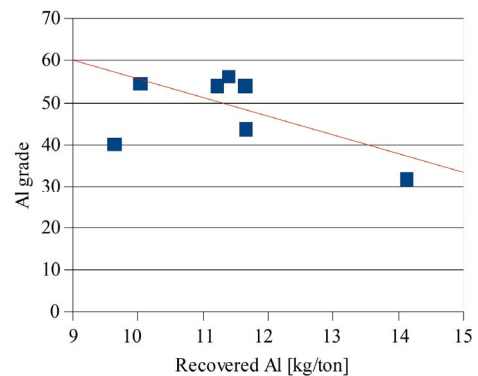


Figure 7. Grade-recovery curve for aluminium in the non-ferrous concentrate stream.

Table 2. Example result for the analysis of a sample from the metal-depleted product stream, including the number of particles (#) found in each split fraction.

Size fraction		Spl.	Aluminium		Heavy non-ferrous		Stainless		Aluminium %	Heavy non-ferrous %	Stainless %
mm	kg		kg	#	kg	#	kg	#			
0 - 2	47.8	256	0.0012		0.00082		0		0.26	0.18	0.0
2 - 5	15.8	8	0.0446	1850	0.0307	344	0	0	0.31 ± 0.01	0.22 ± 0.01	0.0
5 - 20	37.8	2	0.2750	1041	0.188	171	0.014	11	0.48 ± 0.01	0.33 ± 0.03	0.02 ± 0.01
+20	12.8	1	0.0426	19	0.0123	13	0.0564	11	0.04 ± 0.01	0.01 ± 0.00	0.05 ± 0.01
Total	114.2								1.09 ± 0.02	0.74 ± 0.03	0.07 ± 0.02

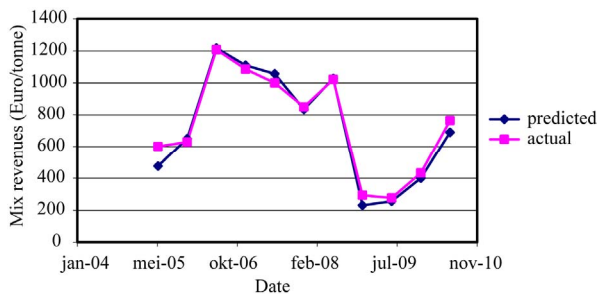


Figure 8. Comparison of actual scrap prices with the predictions of Equation (2).

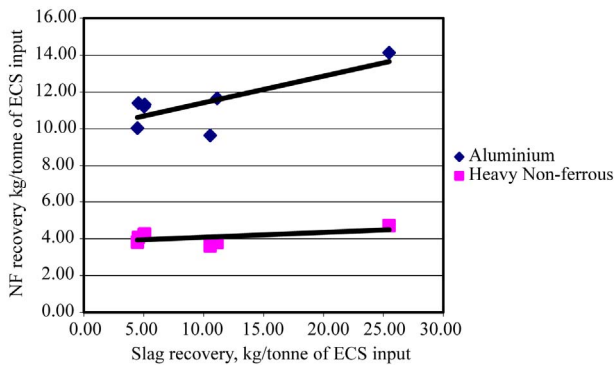


Figure 9. Recovery of non-ferrous metals versus recovery of slag into the non-ferrous product of the ECS.

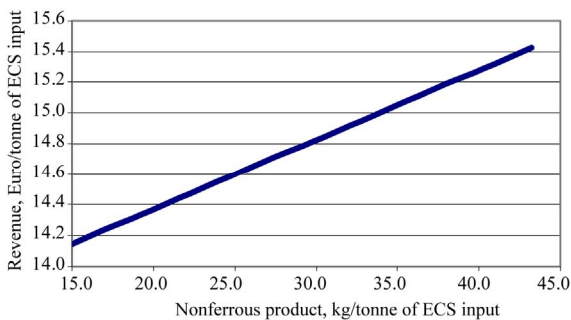


Figure 10. Revenue of the non-ferrous product, per tonne of bottom ash input to the ECS.

Figure 8 shows a comparison of the prediction of this formula against historic scrap revenues for a Dutch MSWI over a five-year period, assuming a sales fee of 10%, a recovery of aluminium from the smelt of 70%, smelter fees of 300 Euro/tonne for aluminium and 900 Euro/tonne for copper and a sink-float fee of 90 Euro/tonne. The land fill fee was set to 0 Euro/tonne, because in this case the slag separated by the sink-floater was returned to the MSWI. During the five-year reference period, the primary data for the non-ferrous concentrate showed a variation in slag content from 10% to 55%, and the LME prices for copper and aluminium varied by a factor of 2. Despite such variations, Equation (2) gives a reasonable account of the fluctuations of the actual non-ferrous scrap revenues obtained by the MSWI. Therefore it is realistic to use such equations in optimization studies, provided that the non-ferrous grade of concentrates remains within the limits of the validation data.

Figure 9 shows the results of the recovery-recovery graph for aluminium and copper versus slag in the non-ferrous concentrate computed from seven experimental data points. The trend line shows a positive correlation between both recoveries. This is expected because changes of the cut-point of the ECS to recover more non-ferrous metals will also increase the amount of slag in the non-ferrous product. However, it is remarkable that 25% more non-ferrous metal can be recovered per tonne of input bottom ash by allowing the slag content of the non-ferrous product to increase from 25% to 58%. **Figure 10** shows a translation of the recovery trend lines into a curve for the revenue per tonne of dry ECS input. The LME prices used in Equation 2 are 1600 Euro/tonne for aluminium and 4,400 Euro/tonne for copper, in correspondence with 2010 trend line figures for these metal prices. The curve indicates that within the range of slag contents covered by the validation data, revenues per tonne of input bottom ash increase with the volume of non-ferrous product (and so with slag content). This means that in order to optimize value recovery, the ECS operator should go for high non-ferrous recovery

and not for high non-ferrous grade. Such a strategy is counterintuitive to most operators but it will increase revenues by up to 8% and is also beneficial for the recycling rate of non-ferrous metals from waste. In this aspect, the result of this study is remarkably parallel to that of a study to optimize non-ferrous value recovery from car scrap, more than a decade ago [13]. That study also concluded that ECS operators may gain 25% extra non-ferrous metals by going for recovery instead of grade, increasing non-ferrous metal revenue by 15%.

REFERENCES

- [1] EU Statistics, "Structural Indicators: Municipal Waste," 2007. <http://Europe.eu.int>.
- [2] L. Muchova and P. C. Rem, "Hydrogen from Bottom Ash," In: A. Kungolos, K. Aravossis, A. Karagiannidis and P. Samaras, Eds., *Proceedings of the International Conference on Environmental Management Engineering, Planning*, GRAFIMA, Thessaloniki, 2007, pp. 1895-1900.
- [3] Y. Hu and M. C. Bakker, "Recovery and Distribution of Incinerated Aluminium Packaging Waste," Submitted to Waste Management, 2010.
- [4] Public Consultation of the European Union, 2006.
- [5] L. Muchova, "Wet Physical Separation of MSWI Bottom Ash," TU Delft PhD Thesis, 2010.
- [6] W. de Vries, P. Rem and P. Berkhout, "ADR: A New Method for Dry Classification," *Proceedings of the ISWA International Conference*, Lisbon, 12-15 October 2009, p. 103.
- [7] J. M. Chimenos, M. Segarra, M. A. Fernandez and F. Espiell, "Characterization of the Bottom Ash in Municipal Solid Waste Incinerator," *Journal of Hazardous Materials*, Vol. 64, No. 3, 1999, pp. 211-222. [doi:10.1016/S0304-3894\(98\)00246-5](https://doi.org/10.1016/S0304-3894(98)00246-5)
- [8] G. Schmelzer, S. Wolf and H. Hoberg, "New Wet Treatment for Components of Incineration Slag," *Aufbereitungs-Technik*, Vol. 37, No. 4, 1996, pp. 149-157.
- [9] L. Muchova, E. J. Bakker and P. C. Rem, "Precious Metals in Municipal Solid Waste Incineration Bottom Ash," *Water Air Soil Pollution*, Vol. 9, No. 1-2, 2009, pp. 107-116. [doi:10.1007/s11267-008-9191-9](https://doi.org/10.1007/s11267-008-9191-9)
- [10] P. C. Rem, C. de Vries, L. A. van Kooy and P. Bevilacqua, M. A. Reuter, "The Amsterdam Pilot on Bottom Ash," *Minerals Engineering*, Vol. 17, No. 2, 2004, pp. 363-365. [doi:10.1016/j.mineng.2003.11.009](https://doi.org/10.1016/j.mineng.2003.11.009)
- [11] BREF Waste Incineration, "Integrated Pollution Prevention and Control: Reference document on the Best Available Techniques for Waste Incineration," July 2005.
- [12] P. Gy, "Sampling for Analytical Purposes," ISBN 0471979562, John Wiley, Hoboken, 1998.
- [13] A. J. Gesing, D. Reno, R. Grisier, R. Dalton and R. Wolanski, "Nonferrous Metal Recovery from Auto Shredder Residue Using Eddy Current Separators," In: B. Mishra, Ed., *Proceedings of the EPD Congress*, 1998, TMS (1998) 9.