BOTTOM ASH FROM WTE PLANTS
METAL RECOVERY AND UTILIZATION
This report has been written for ISWA – Working group on energy recovery.

The front page picture shows non-ferrous metals heavier than aluminum (copper, brass, silver, gold…) in the size 0.2 - 0.7 mm, recovered from municipal solid waste incineration bottom ash.

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CONTENTS

1. Executive Summary 4
2. Introduction 5
3. Metals and incineration 6
  3.1 Metal behavior during incineration 6
  3.2 Bottom ash discharge 8
  3.2.1 Wet bottom ash discharge 8
  3.2.2 Dry bottom ash discharge 8
  3.2.3 Bottom ash washing 10
4. Metals in bottom ash 11
  4.1 Metal content and value 11
5. Metal Recovery Technology 13
  5.1 Magnetic separation 13
  5.2 Sieving 13
  5.3 Eddy Current Separation 14
  5.4 Sensor technology 15
  5.4.1 Induction Sorting System 15
  5.4.2 X-ray sorting 15
  5.5 Crushing/milling 16
  5.6 Other separation techniques 16
  5.7 Examples of modern metal sorting systems 16
6. Bottom ash utilization 20
  6.1 Mechanical properties 20
  6.2 Weathering 20
  6.3 Examples of utilization 21
  6.4 Environmental considerations 22
7. Market volumes 23
8. Market Trends 26
9. Barriers for bottom ash utilization and metal sorting 27
10. Works Cited 28

APPENDICES
Appendix 1
Estimated concentration of gold and silver in bottom ash
1 EXECUTIVE SUMMARY

Seeking to better integrate Waste-to-Energy (WtE) technology as part of a circular economy, it is beneficial to make use of the solid residues and extract metals for recycling. By doing so, the stream of materials and energy that are otherwise landfilled, and thus not utilized, is minimized. Recycling of extracted metals and utilization of bottom ash will substitute the mining and manufacturing of virgin material, thus lowering the burden on natural resources and serving as a valuable complement to high quality material recycling.

The increased awareness on resource recovery potential of the bottom ash has caused great developments. Developments which include more efficient separation techniques and alternative process solutions.

The scope of this report is to give an overview of the mechanisms occurring during incineration, which influence metal recovery potential and describe basic concepts in bottom ash sorting technology and preparation for bottom ash utilization. Furthermore, it is the goal to identify promising developments, as well as areas which could benefit from further research.

The technical description of WtE or metal sorting technology is brief. For detailed technical information, the reader is referenced to suppliers of such equipment.

The report is not considered as being a complete technical evaluation. It is rather a compilation of information gathered among the members of ISWAs Working Group on Energy Recovery, in order to give a brief yet good understanding of the current capabilities, recent developments and expected future trends.
2 INTRODUCTION

The largest solid waste stream from WtE is the inert fraction of the waste. The inert fraction comprises of different materials and is collectively referred to as bottom ash. For each incoming tonne of mixed Municipal Solid Waste (MSW), about 180-250 kg of bottom ash is generated. Bottom ash consists of primarily Silicon, calcium, iron, aluminum and sodium. Table 1 presents the approximate composition of bottom ash.

It is important to note that the composition presented in Table 1 is based on an elemental analysis. An elemental analysis does not specify the chemical form in which each element occurs. This is especially of importance when focusing on metal recovery, as a large part of the metals will naturally occur in an oxidized form. An example hereof is aluminum, which, in oxidized form is one of the most abundant materials on earth. Aluminum oxide is highly represented in waste fractions containing ceramics, clay etc.

The appearance of bottom ash is a mix of a very fine grey porous material, inert components such as fine gravel, rocks, glass, ceramics and metallic items.

The amount of metallic items that can be separated from the bottom ashes vary, depending on the incoming waste composition. In literature, ferrous metals account for 7-15 % of the bottom ash weight, whereas non-ferrous account for 1-2 % of the bottom ash weight (Sabbas, et al., 2003), (Baun, Kamuk, & Avanzi, 2007). Such metals that appear in the bottom ash in metallic form are often removed from the bottom ash using various separation techniques.

Removal of ferrous metals has been carried out for many years using magnets. Removal of non-ferrous metals is currently practiced in some countries, and the technology for recovery of non-ferrous metals has undergone tremendous development in recent years. The development has been driven by rising metal prices and the realization that bottom ash can be considered as a high concentration metal ore. The energy consumption of a sorting plant is very small compared to the energy savings from recycling. Hence, the environmental impact of a sorting plant is almost negligible. Furthermore, removal of the metal items, especially aluminum, improves the mechanical properties of the bottom ash as a sub-base material for road construction purposes.

Whether or not the mineral fraction of the bottom ash is disposed or utilized varies in different countries. For example, in Denmark and the Netherlands, the mineral fraction has primarily been used for construction purposes in roads and embankments whereas Switzerland primarily landfills their mineral fraction of the bottom ash.

Legislation ensures that the leachate of pollutants, such as salts and heavy metals, are kept at acceptable levels to reduce environmental impact. The fate of the bottom ash is usually a result of legislation.

<table>
<thead>
<tr>
<th>Element</th>
<th>unit</th>
<th>range</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>g/kg</td>
<td>168-274</td>
<td>221</td>
</tr>
<tr>
<td>Calcium</td>
<td>g/kg</td>
<td>89.1-104</td>
<td>94.9</td>
</tr>
<tr>
<td>Iron</td>
<td>g/kg</td>
<td>46.7-77.8</td>
<td>65.1</td>
</tr>
<tr>
<td>Aluminum</td>
<td>g/kg</td>
<td>45.0-56.1</td>
<td>50.3</td>
</tr>
<tr>
<td>Sodium</td>
<td>g/kg</td>
<td>33.3-39.2</td>
<td>35.4</td>
</tr>
<tr>
<td>Magnesium</td>
<td>g/kg</td>
<td>10.5-11.2</td>
<td>10.7</td>
</tr>
<tr>
<td>Potassium</td>
<td>g/kg</td>
<td>7.4-8.6</td>
<td>8.1</td>
</tr>
<tr>
<td>Copper</td>
<td>g/kg</td>
<td>3.4-11.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Zinc</td>
<td>g/kg</td>
<td>2.0-4.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Barium</td>
<td>g/kg</td>
<td>1.1-2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Lead</td>
<td>g/kg</td>
<td>0.6-2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Silver</td>
<td>mg/kg</td>
<td>-</td>
<td>19.9</td>
</tr>
<tr>
<td>Gold</td>
<td>mg/kg</td>
<td>-</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 1 Approximate composition of bottom ash, in mass percentages, sources: (ISWA, 2006), (Astrup & Christensen, 2003). Silver and gold values estimated from results presented in (Morf, et al., 2013), see Appendix 1.
Many countries practice separate collection of clean metals for recycling. Separate collection is primarily done for relatively large objects, such as metal lamps, cutlery, tin and aluminum cans. As such, these metal items are not considered as part of MSW for incineration. However, small amounts of these items are commonly seen in the bottom ash as a result of lack of sorting or because it is difficult and resource demanding to separate.

Most of the metals mined from bottom ash originate from a composite product, where the metallic material is troublesome or nearly impossible to separate. Examples hereof are nails in wood, zippers from clothing, copper wire bits, stainless steel ball point pen tips, gold soldering in electronic circuit boards, etc.

The metals present in the bottom ash originate from the incoming waste composition. During the incineration process, metals will evaporate, burn, oxidize or, in most cases, remain in metallic form. If the latter is the case, the metal can be recycled using current recycling practice.

It is a common misconception that metals are of lesser value when they have gone through the incineration process. This is not the case for metals that remain in metallic form. Furthermore, tin cans containing food leftovers, a paper label and plastic coating inside will have to undergo multiple process steps of purification when sent directly to recycling. In the incineration process the plastic, paper and food will burn, turning into usable energy. The tin can thus undergoes a cleaning process that has a positive energy benefit, prior to being recycled.

In general, an important reason for incinerating waste is the mass and volume reduction. A reduction that results in less space necessary if the alternative is landfilling. The mass and volume reduction also plays an important role with regard to separation of metals. The incineration process converts the incoming waste from a complex mixture of low-grade materials, to a somewhat simple mixture of reduced mass and volume. This reduction and homogenization makes finding „the needle in the haystack“ much easier.

The presence of metals in a metallic form in bottom ash depends on various factors, as there are multiple parameters that affect the fate of the metal. Parameters of known influence and parameters that have yet to be quantified are described in this chapter.

### 3.1 Metal Behavior During Incineration

Many papers have investigated the behavior of volatile metals during the incineration process. Mercury and cadmium are important examples of volatile metals that have been thoroughly studied in view of their influence on human health. Only in recent years more focus on the behavior of non-volatile metals suitable for recycling has evolved. Examples of these metals suitable for recycling are iron, aluminum, copper, tin, zinc, lead, silver, gold and various alloys.

Laboratory test show that, for aluminum, the most influential factors for metallic aluminum losses are material thickness, combustion temperature, residence time and salt contamination (Hu, Bakker, & de Heij, 2011).

A study of the behavior of different types of aluminum packaging in a full scale WtE facility has been carried out in Northern Italy. The study found that the amount of aluminum products going through the incineration process without deteriorating, ranged from around 40% for very thin foils (10-42μm) up to over 90% for cans (90-25μm) (Biganzoli, 2012). The aforementioned study was conducted at incineration plants with wet bottom ash discharge. The mass balance of the study was based on the input and output of the WtE line. Thus, the losses cannot be tied to a specific
process step, e.g. losses tied to the incineration process or the wet bottom ash quench.

One of the main causes of losses of metals during incineration is believed to be oxidation. For oxidation to occur, it is required that the metals in the waste are in contact with oxygen. Modern WtE facilities carefully control the conditions at which the waste is incinerated i.e. controlling the supplied combustion air (primary/secondary air) and waste layer thickness. By carefully controlling these parameters, it is ensured that the processes that occur in the actual waste layer are pyrolysis and gasification, and that the complete combustion occurs above the waste layer, following supply of secondary air. This means that non-oxidizing conditions exist in the waste layer, as the oxygen supplied by primary air (in the waste layer) will react with the volatile organic matter prior to reacting with metals.

Metals willingness to react and change form is in basic chemistry ranked in a so-called reactivity series. The reactivity series for metals is shown in Figure 2. The weakest base metals (K, Ca, Na) will react with water whereas other base metals will need to be in contact with acids. Only very strong acids will react with Ag, Au and Cu.

The reactivity series gives a good indication of which metals will be most affected by the incineration process. Another important factor is of course the respective metals boiling point. Mercury (Hg) has a boiling point of 357°C, which is well below the temperature in the furnace. Consequently, the amount of mercury occurring in the bottom ash is negligible.

Figure 3 shows non-ferrous metals with a higher density than aluminum (Cu, Au, Ag, Pb, Sn, Zn), in the size range 0.2 - 0.7 mm. The metals have been sorted from a dry bottom ash. There is very little sign of oxidation. As the items are of very fine size the (very high specific surface area) and the degree of oxidation is very low, there’s no reason to believe that the incineration process significantly deteriorates these metals.

Metals with a low melting point, such as aluminum or zinc, will experience melting and drip to the lower layers of the waste where it will again solidify as the temperature drops. Figure 4 shows a lump of aluminum from incineration. The lump has an embedded glass shard and a complex shape indicating melting. The lump is the size of a golf ball and shows low degree of oxidation.

The metals in Figure 3 and Figure 4 both derive from plants with dry bottom ash discharge, see section 3.2.
3.2 BOTTOM ASH DISCHARGE

Two main types of bottom ash discharge systems exist – a wet and a dry. The two discharge systems are described below.

3.2.1 WET BOTTOM ASH DISCHARGE

The wet bottom ash discharge is the most commonly installed bottom ash discharge system. Two main designs exist, yet the basic principle is the same. As the inert fraction reaches the end of the moving grate, it falls into a water bath. The quenching ensures that burning lumps are extinguished, cools the bottom ash making later handling easier and minimizing dust issues. Furthermore, the water level can be set in an appropriate height ensuring an air tight seal from the surroundings to the furnace. The bottom ash is mechanically removed as needed, either by a pressure piston (Ram discharge) or by a chain transport system. Figure 5 shows a sketch of a wet bottom ash discharge system with a discharge ram.

![Figure 5 Principle sketch of the wet bottom ash discharge system with discharge ram.](image)

The discharge ram, depicted in Figure 5, pushes the quenched bottom ash batch wise out of the discharge system and onto conveyor belts leading to a bottom ash bunker/silo. The cadence of the discharge ram can be regulated by timer or by the height of bottom ash in the shaft using sensor techniques. Some installations use a chain belt conveyor to continuously remove the quenched slag.

The water in the wet bottom ash discharge system will be an alkaline environment. To what degree the alkaline environment effects metal recovery potential has yet to be scientifically quantified. The effect will vary for different metals/alloys as well as the size and shape of the metal.

3.2.2 DRY BOTTOM ASH DISCHARGE

In dry bottom ash discharge, the slag is discharged without the use of water. Consequently, the metals are neither quenched nor introduced to an alkaline environment. Furthermore, the mineral fraction of the bottom ash will not ‘lump’ together, making later separation of metals and mineral fraction easier.

Dry bottom ash discharge was the predominant slag extraction until the 1990’s, where they were replaced by wet systems to avoid dust problems. Recently, the focus on metal recovery has revived the dry system. However, careful considerations have to be made to prevent a dusty working environment. In a dry system, it is necessary to handle the bottom ash in a fully enclosed system with constant suction ensuring a slight vacuum. If the enclosure is designed properly, it is possible to obtain a low-dust environment when the plant is in operation. Challenges will inevitably exist when the enclosure is opened and vacuum cannot be achieved, such as during maintenance.

Two modern dry slag extraction systems are described in this report. Both of them are located in Switzerland and have different designs.

The SATOM plant in Monthey, Switzerland, has converted a wet discharge system as depicted in Figure 5. The conversion means running the discharge system without water addition. As the bottom ash leaves the discharger it enters a wind sieve. The wind sieve is a vibrating conveyor, where the bottom ash falls across different levels with suction in the opposite direction of the movement. Please see Figure 6.

![Figure 6 Bottom ash discharge system with wind sieve installed.](image)
Figure 7 shows a simplified process flow diagram. The air suction through the wind sieve separates the light airborne fraction of the bottom ash. The suction is caused by the secondary combustion air fan.

The dust is separated from the air stream using a cyclone, prior to being used as secondary combustion air. As part of the secondary combustion air is drawn through the wind sieve, the air is preheated by the warm bottom ash.

The coarse bottom ash is removed by conveyor belts and the remaining fraction is sent for further sorting.

Another dry bottom ash discharge system is installed at the KEZO plant in Hinwil, Switzerland.

This discharge system consists of a vibrating conveyor where the bottom ash is cooled by so-called tertiary air. The tertiary air is limited by vertical gates and driven by a slight vacuum in the furnace. The flow of tertiary air is approximately 500 Nm³/tonne waste.

At the end of the vibrating conveyor, the bottom ash is fractioned by a perforated floor, thus separating the bottom ash into fraction above and below 5 mm. The vibrating conveyor is shown in Figure 8.

The fraction below 5 mm is fractioned at the end of the vibrating table and sent for further sorting.
3.2.3 BOTTOM ASH WASHING

The Belgian company Indaver offers a wet treatment process, where the extracted bottom ash is washed with excess water from flue gas cleaning in a special washer barrel prior leaving the facility. A simplified diagram of the process is shown in Figure 9.

The washing releases some organic material, which is removed and re-introduced to the incineration process. Metals in the bottom ash are removed after the washing process using regular wet separation technology, as described in section 5. The purpose of the washing process step is to reduce trace element content and subsequent leaching during landfilling/utilization. In the Indaver process, the bottom ash below 2 mm does not undergo metal separation. Consequently, in the Indaver case the metal content in this fraction is currently not recovered.
4 METALS IN BOTTOM ASH

4.1 METAL CONTENT AND VALUE

Determination of the metal recovery potential by hand sorting has been standardized in the European Union by EN 1744-8. The standard specifies principle, necessary sample size, apparatus and procedure. The potential for metal recovery can also be based on chemical analysis. However, chemical analysis will typically show total content, thus not distinguishing between metals in a metallic, ionic or oxidized form.

Only metals in metallic form have recycling value using current metal recycling practice.

Larger ferrous metals are almost always sorted out for recycling at the plant. Systems for recovery and recycling of non-ferrous metals, and small ferrous objects, is becoming increasingly common but have yet to reach its full potential.

Figure 10 shows the non-ferrous metals presence in different size fractions. The recovered metal types are generally found in all fractions. Gold is primarily present in the small fractions, as gold in MSW primarily arise from fine electronics, such as soldering on electronic circuit boards.

In terms of mass, iron comprises most of the metal present in bottom ash followed by especially aluminum. In terms of value, however, precious metals present in small quantities are of high economic importance.

The amounts of some selected metals found in the before mentioned study, as well as the approximate scrap value of each selected metal, is listed in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Metal</th>
<th>Amount [kg/tonne]</th>
<th>Estimated scrap price [€/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>31.4</td>
<td>0.12</td>
</tr>
<tr>
<td>Al</td>
<td>16.1</td>
<td>0.80</td>
</tr>
<tr>
<td>Cu</td>
<td>2.2</td>
<td>4.00</td>
</tr>
<tr>
<td>Zn</td>
<td>0.9</td>
<td>0.73</td>
</tr>
<tr>
<td>Pb</td>
<td>0.3</td>
<td>1.07</td>
</tr>
<tr>
<td>Ag</td>
<td>0.004</td>
<td>270</td>
</tr>
<tr>
<td>Au</td>
<td>0.0004</td>
<td>27600</td>
</tr>
</tbody>
</table>

In a study performed at the KEZO plant in Switzerland, it was found that 32 kg of iron could be found per tonne of waste input whereas the gold content was about 0.4 grams per tonne (Morf, et al., 2013). Even though iron content comprises most of the recoverable metals, the economic value of the iron is roughly 10% of the total metal value, whereas the small amount of gold comprises almost 30% of the total metal value.

Figure 11 shows the mass and value distribution of selected metals, based on metal content found in the bottom ash of the KEZO WtE facility (Morf, et al., 2013).

Figure 10 Non-ferrous metal yields in different size fractions. Divided into aluminium and heavies (Cu, Au, Ag, Zn etc.).
As seen in Figure 11, it is quite evident that for the KEZO plant, metals such as copper and gold comprise a significant value, although present in very small quantities. The gold is mostly present in the very fine fractions. Generally, the majority of copper and gold is expected to arise from waste electronics.

Metals from WtE plant with wet slag extraction will be coated with a thin layer of solidified mineral material (oxides of Silicon and Calcium). This coating will not appear on slag from dry bottom ash. The difference is shown in Figure 12.

The mineral layer on metals from wet bottom ash can be removed using acid. However, according to experience gained at the SCANMETALS upgrading plant in Denmark, this process step is not necessary, as the value of metals does not increase if cleaned prior to re-melting.
5 METAL RECOVERY TECHNOLOGY

5.1 MAGNETIC SEPARATION

Magnetic separation is one of the first steps in the bottom ash sorting system. The magnetic separation removes ferrous metals. Although stainless steel alloys main element is iron, the alloys available are practically speaking non-magnetic. Therefore, stainless steel cannot be removed using magnetic separation.

There are many different types and setups of magnetic separation. The most common in bottom ash sorting are magnetic drum and overhead suspension magnets. The two types can be seen in Figure 13.

The setup of the magnets varies depending on the material flow, particle size, magnet strength and size and material velocity. The advantages and suggested setup is beyond the scope of this report.

5.2 SIEVING

A very important step in the removal of metals is an accurate fractioning of the bottom ash. Having accurately defined fractions allows to optimize the sorting of metals.

The sieve type chosen in the sorting system depends on the sizing. For large oversized items, it is common to install a simple finger sieve. The oversized items are removed using a finger sieve are typically manually sorted, as the metalling items in this sizing are relatively rare and easily identified.

Drum sieves are used for intermediate size fractioning, and consist of a rotating perforated steel cylinder. Drum sieves are typically used early in the sieving.

Figure 13
(A) Magnetic drum
(B) Overhead suspension magnet. The overhead suspension magnet is installed orthogonally to the belt conveyor moving the stream of bottom ash.

Figure 14
(A) Finger sieve at end of vibrating table for removal of oversized items.
(B) Drum sieve for intermediate fractioning.
Flip flow screens are commonly used for the fine fractioning of wet bottom ash. A flexible perforated rubber screen moves in an oscillating manner, while the material travels across the screen. The shaking ensures that the material is mixed and allows the fine fraction to pass through the perforations.

Similar to the flip flow screen is the vibrating screen, where the sieve vibrates instead of oscillating.

Both the flip-flow screen and the vibrating screen can have multiple fractioning stacked above each other, minimizing space requirement. **Figure 15** shows such a flip flow screen with multiple fractioning steps and the principal movement of the screen (oscillation).

Sieving and transport of wet bottom ash can generally be done in open systems, although this is not a fully dust free operation. Wet sorting systems aim to ensure a water percentage of 10-12%. If the water percentage is higher, difficulties arise when sieving due to lumping of the bottom ash. Lumping of bottom ash significantly affects the subsequent metal sorting. This is especially the case for the fine fraction, where the high value metals are present.

If the water percentage is lower than 10%, the working environment will begin to become too dusty. Sieving can be carried out enclosed to avoid dust. Enclosed vibrating screens are used in the dry sorting system described in section 5.7.

In order to have an effective sorting of non-ferrous metals, it is vital to have a precise fractioning of the bottom ash.

### 5.3 EDDY CURRENT SEPARATION

Eddy current separation is a technique for separating non-magnetic metals from a material stream. The eddy current machine consists of a conveyor with a non-magnetic drum. The drum is equipped with an internal rotating set of magnets. The magnets inside the drum create repulsive forces, pushing non-ferrous metals on a path away from the drum. Please see **Figure 16**.

The ballistic curve of the non-metallic objects is a result of the gravitational, centrifugal, friction (with belt) and drag force (air resistance). Metallic objects are, among the before mentioned forces, affected by a magnetic deflecting force, that is caused by interaction of eddy currents induced in conductive materials. The eddy currents are created by the internal rotating magnets. Metals will have a more flat ballistic curve than the non-metallic material. Separation of the two types can thus be done by a screen set in a proper distance.

The theoretical curve of different objects is hard to predict. However, the magnitude of the magnetic deflection force is highly related to the ratio of electrical conductivity and density, hereinafter referred to as repulsiveness. The repulsiveness of different metals is presented in **Table 3**.
With the previously mentioned forces in play, the ballistic curves will be more predictable for equal sizes. For this reason, a precisely defined interval in the fractioning as well as a properly chosen dimension span is the most important factor on the effectiveness of the Eddy Current Separation.

Furthermore, having multiple Eddy Current Separators in series will increase the overall effectiveness. Experiences at the ZAR facility showed, that two Eddy Current Separators in series installed in an inclined angle increased the overall sorting efficiency from 75 % to 82 % (Stiftung Zentrum Für Nachhaltige Abfall- Und Ressourcennutzung (ZAR), 2011). Modern ECS machinery can thus be very effective.

### 5.4 SENSOR TECHNOLOGY

#### 5.4.1 INDUCTION SORTING SYSTEM

Stainless steel is practically speaking non-magnetic. Furthermore, the conductivity of steel is low, resulting in a low repulsiveness, as presented in Table 3. Consequently, stainless steel can in practice not be sorted using magnets or eddy current technology. Stainless steel can however be sorted using sensor technology.

When using an Induction Sorting System (ISS), metallic objects are detected using magnetic induction. When a metallic object is located on the conveyor belt in the ISS, the object is removed from the stream by a pulse of compressed air, as the object is thrown over the conveyor belt edge.

The ISS will typically be installed as the last sorting system after magnetic separation and Eddy Current Separation.

#### 5.4.2 X-RAY SORTING

The working principle of X-ray sorting is very similar to the ISS sorting system as presented in section 5.4.1. Instead of a sensor detecting metallic items and X-ray module is installed, recognizing specific shapes that most likely will be metallic, such as flat round objects (coins, washers etc.). The recognized objects are mechanically removed from the stream using a pulse of compressed air.

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**Table 3** Conductivity, density and resulting repulsiveness of different metals.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Conductivity ([1/\Omega m])</th>
<th>Density ([\text{kg/m}^3])</th>
<th>Repulsiveness ([\text{m}^2/\Omega \text{kg}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>37000000</td>
<td>2700</td>
<td>13704</td>
</tr>
<tr>
<td>Copper</td>
<td>59900000</td>
<td>8960</td>
<td>6685</td>
</tr>
<tr>
<td>Silver</td>
<td>62100000</td>
<td>10500</td>
<td>5914</td>
</tr>
<tr>
<td>Zinc</td>
<td>16900000</td>
<td>7140</td>
<td>2367</td>
</tr>
<tr>
<td>Gold</td>
<td>41700000</td>
<td>19320</td>
<td>2158</td>
</tr>
<tr>
<td>Iron</td>
<td>10300000</td>
<td>7870</td>
<td>1309</td>
</tr>
<tr>
<td>Bronze</td>
<td>7100000</td>
<td>8900</td>
<td>798</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>1400000</td>
<td>7800</td>
<td>179</td>
</tr>
</tbody>
</table>

---

Figure 17 Working concept of an Induction Sorting System (ISS).
5.5 CRUSHING/MILLING

Some sorting plants boost their metal separation performance by crushing/milling the bottom ash. By doing so, mineral fractions sticking to metals lumps are removed and large lumps of minerals are pulverized.

The drawback of crushing and milling is the change to the mechanical characteristics of the bottom ash. Crushing and milling is therefore rarely seen, or only done to a small extent, if the mineral fraction is used for road construction.

5.6 OTHER SEPARATION TECHNIQUES

The Dutch company INASHCO has in collaboration with the Delft University of Technology (TU Delft) developed a separation technique, in which ballistic separation is used to separate the fine, soft and light minerals with the hard and heavy metals/rocks. The separation apparatus is called Advanced Dry Recovery (ADR).

The ADR used by INASHCO deals with the fraction in the 0 - 2 mm size. The principle of the ADR is depicted in Figure 18. The apparatus lets the bottom ash stream fall onto a turning bladed drum. As the bottom ash is struck by the drum blades, the different components of the bottom ash (mineral fraction, rocks and metals) will obtain different ballistic paths. Furthermore, the different ballistic paths are assisted by a downward blowing jet stream. The light components (mineral fraction) will fall down to the first conveyor belt exiting the apparatus. The heavy components (rocks and metals) will experience a more flat ballistic curve and therefore land on the second conveyor belt. The air jet separation is repeated to increase purity of the separated stream. The fine, light and soft components and the hard and heavy components will thus be separated. The ADR works most efficient following a precise size fractioning and prior to ECS separators.

The INASHCO company handles metal extraction for some European WtE installation. The company claims high sorting efficiencies, albeit documentation has yet to be disclosed to the public.

Other unique sorting systems exist that are not described in this report, e.g. LAB Geodur.

5.7 EXAMPLES OF MODERN METAL SORTING SYSTEMS

This section gives two examples of some modern sorting systems, using some of the described technology.

Wet sorting system
The central bottom ash treatment plant AFATEK in Copenhagen, Denmark, will in 2015 realize a new modern wet sorting system with multiple processing steps. The raw bottom ash from incineration plants will undergo sorting and 1 to 2 months of weathering, before being used in road construction.
The sorting system is designed to handle bottom ash with a water content of 10-15%. AFATEK has experienced that monitoring water content is of importance, as it affects the downstream sorting process performance. Low water content in bottom ashes makes sieving easier. However, more care must be taken with regard to dust handling as the water content is lowered.

**Figure 19** shows a process flow diagram of the planned facility, which is a development of an existing facility.
As seen in Figure 19, the raw bottom ash enters the sorting facility and, at first, undergoes pre-sorting. In pre-sorting, bulky and oversized objects (> 300 mm) are removed from the stream and manually sorted. Large inert objects larger than 50 mm are crushed and reintroduced into the sorting system. Organic material recovered is sent back to incineration for energy recovery.

Large ferrous metal objects are recovered in pre-sorting using magnets.

If the water content of the bottom ash is higher than 10-15 %, interim storage/weathering is necessary to lower the water content.

Ferrous metals recovered in pre-sorting are sent for a series of upgrading processes, in which any mineral material attached is mechanically removed. The upgraded items are sent for recycling, whereas the mineral fraction is reintroduced into the sorting system.

The bottom ash fraction smaller than 50 mm, with most ferrous objects removed, is sent for non-ferrous metal sorting. In non-ferrous metal sorting, the bottom ash is sieved into five size fractions (18 - 50 mm, 9 - 18 mm, 4 - 9 mm, 1.6 - 4 mm and 0.5 - 1.6 mm). Each fraction passes a magnet, for additional removal of ferrous metals, and two steps of ECS removing non-ferrous metals.

After the ECS, the fraction from 4-50 mm is sent through an ISS, removing stainless steel. Recovered stainless steel is sent for upgrading.

The existing plant recovers about 75 % of the metal items present in the raw bottom ash. The new plant, depicted in Figure 19, expected to recover 90 % of the metal items present in the raw bottom ash. The removed metals are sent to recycling, whereas the remaining mineral fraction weathered, prior to being utilized. Utilization in Denmark is currently primarily in road construction.

Dry sorting system

Figure 20 shows the sorting system installed at the ZAR sorting facility, treating fine bottom ash from the KEZO plant, which have a modern dry extraction system installed. The coarse bottom ash, larger than 5 mm, is wetted and treated externally, similarly to the process described in section 5.7.

As depicted in Figure 20, magnetic iron is first separated from the discharged bottom ash (< 5 mm) before temporary storage in a collecting silo. The purpose of the storage silo is to act as a buffer in the system.

The bottom ash is first sieved in an enclosed vibrating screen into the fractions 0.7 - 5 mm and 0.2 - 0.7 mm. The 0.7 - 5 mm fraction first undergoes removal of fine magnetic iron by use of a magnet. The removed iron is disposed of along with the bottom ash. After removal of the magnetic iron, the stream undergoes two steps of ECS separation for removal of non-ferrous metals. The mineral fraction of the bottom ash is led to a silo. The stream of non-ferrous metals, separated by the ECS, is further divided into 0.7 - 3 mm and 3 - 5 mm fractions using a sieve. Each of these two streams are fed into separating tables, which are able to separate the non-ferrous metal into aluminum and a mixture of other non-ferrous metals (primarily Cu and some Zn, Au, Ag etc.). The separation tables separate the metals based on their density.

The 0.2 - 0.7 mm fraction separated in the first sieving undergoes a secondary sieving. This is done to ensure a precise cut, making subsequent metal extraction more efficient. The stream undergoes one step of magnetic separation and two stages of ECS prior to separation into aluminum and a mixture of other non-ferrous metals. The mineral fraction is, after the ECS separation, led to the same silo as the 0.7 mm fraction.

The sorting system is fully enclosed and kept in a slight vacuum, ensuring that the working environment is virtually dust free.
Figure 20 shows the sorting system at the ZAR facility, treating dry bottom ash from the KEZO plant. The course bottom ash (> 5 mm) is wetted and handled externally.
After removal of metals, bottom ash is either landfilled or utilized for construction purposes. As a construction material, bottom ash has especially been used as a sub base material in road construction, substituting virgin gravel material. Other forms of utilization can be used in low-tensile strength concrete products, decreasing demand for energy intensive concrete production. This section presents some uses, process steps for use and some environmental considerations.

6.1 MECHANICAL PROPERTIES

The mechanical properties of bottom ash have been thoroughly studied in several countries. Generally speaking, the quality of the bottom ash is high, making the ash suitable as a substitute for sand and gravel as a sub-base material.

The grain size distribution plays an important role for the utilization possibilities of bottom ash. Experience has shown that utilization suitability is, among other factors, correlated to its grain size distribution curve. Figure 21 shows a typical grain size distribution curve, taken from bottom ash to be utilized in road construction.

Following fractioning for metal separation, as described in section 5, it is vital to re-combine and mix the fractions and to systematically test the grain size distribution. For sorting processes that include crushing/milling the grain size distribution curve will be affected. The options for utilization of the bottom ash typically dictate whether or not crushing/milling is performed.

Research has also shown that increased content of iron and aluminum oxides increases the mechanical strength of bottom ashes (Weng, Lin, & Ho, 2010).

6.2 WEATHERING

Weathering (or aging) is a relatively simple treatment done prior to or after metal separation. Weathering is the combination of CO₂ uptake from the atmosphere and chemical reactions following contact with water. Contact with water due to the wet slag extraction or wetting after dry slag extraction.

Proper weathering can effectively be achieved by storing the bottom ashes with good access to air, water and occasional turning. Figure 22 shows stockpiles of bottom ash during weathering.

By ensuring weathering is done prior to utilization or landfilling, the reactivity of the bottom ash and the leaching of metals are reduced. This is due to:

- Mineralogical and geochemical changes due to uptake of CO₂ (carbonation) and thereby lowering of pH (typical from pH 11 - 12 to pH 8 - 10)
- Hydration and other changes in the mineral phases in the bottom ash
- Binding/sorption of dissolved elements (especially heavy metals) to the matrix of the bottom ash
- Removal or transformation of available organic ligands, e.g. by evaporation, leaching, or changes in the binding characteristics
- Leaching of highly dissolvable salts

Research has shown that the concentration of
various components in leachate follows the pH value of the leachate (Zhang, He, Shao, & Li, 2008). Concentration of Copper in leachate has also been shown to be strongly correlated to the amount of dissolved organic carbon (van Zomeren & Comans, 2004).

Leachate collected during weathering has a relatively high concentration of soluble salts and minor amounts of metals. Typically, the bottom ashes are weathered until the chemical reaction with water goes from strongly alkaline to somewhat neutral. It takes 6 - 20 weeks of weathering before the ash is chemically stable and suitable for utilization or landfilling (Astrup & Christensen, 2003) (Hjelmar, Holm, Lehmann, Asmussen, & Rose, 1998).

At the AFATEK facility, collected leachate from weathering is reused at the facility in a closed loop manner. Hence, there is no need for treatment of leachate or discharge of wastewater. Water for weathering comes solely from rainwater.

Besides improving the leaching properties of the bottom ash, weathering improves the mechanical properties as the bottom ash becomes chemically stable.

To facilitate the chemical reactions occurring, and to avoid dust during weathering, it is necessary that the bottom ash is wet. Consequently, the dry system as described 3.2.2 would have to be wetted after the metal sorting process, prior to weathering.

### 6.3 EXAMPLES OF UTILIZATION

Weathered bottom ash has primarily been used as a sub-base material for road construction, substituting virgin gravel and sand material. For this application, the material specification and testing of functional specifications has been standardized in EN 13285 and EN 13242.

When used as a sub base material, it is usually ensured that there is no hydraulic contact with the surface, keeping the amount of leaching possible to a minimum.

Denmark has for many years used bottom ash as a sub-base material in road construction. Experience has shown that virgin gravel from Danish mines is more resistant to abrasion than bottom ash. However, experience has also shown that bottom ash is capable of supporting a heavier load than virgin gravel. This is believed to be due to the non-uniform surface, compared to gravel which has a more uniform, almost fully round surface. Non-uniform surfaces allow normal forces from loading to dissipate as normal and shear forces, thus distributing the load in multiple directions.

With the realization above, Danish legislation has since 2012 allowed for incineration ashes to be used in roads with a high load. Research is being carried out, aiming to allow for incineration ashes to be used in road construction without load restrictions.

France, Germany and the Netherlands are examples of European countries that also utilize bottom ash from waste incineration as a sub-base material for road construction. In all countries, the degree of contamination of the leachate is tested prior to utilization. The limits for utilization and test method vary by country, why a direct comparison is not possible. However, the degree of utilization is high in all cases. Interested readers are referred to (ISWA, 2006).

In Switzerland bottom ash is generally landfilled and thus not utilized. However, the finer fraction of bottom ashes is in some cases utilized in fly ash stabilization. In fly ash stabilization, cement and water is mixed with the fly ash, creating a solid chemically inert concrete block. By mixing the fine
fraction of the bottom ash with the fly ash, less cement must be added in order for the mixture to solidify and stabilize the fly ash. The demand for virgin produced cement is thereby lowered.

Concrete products with low tensile strength can also be produced using bottom ashes. Figure 23 shows concrete tiles produced using wet bottom ash.

The concrete tiles shown in Figure 23 are from tests carried out at a Danish factory, producing various concrete products. The bottom ash concrete tiles shown in Figure 23 have yet to be commercialized. In Denmark, roughly 3 million tonne of concrete products are produced annually. It is estimated that for this amount of concrete products, 1.3 million tonne of virgin cement production can be avoided by utilizing bottom ash (Kallesøe, 2012).

Bottom ash from incineration can also be used as highway embankments/noise barriers. Along the A12 highway in the Netherlands, bottom ashes from Dutch incineration plants are the primary material for more than 1 km of noise barrier.

For all possible types of utilization, it is beneficial for the mechanical properties that the metal sorting prior to utilization is as efficient as possible. Removing all metals creates a very homogenous and mechanically strong material.

6.4 ENVIRONMENTAL CONSIDERATIONS

With regard to toxicity to water and soil, the environmental impact of using bottom ash in road construction has been shown to be comparable with disposal of bottom ash in controlled landfills. The saving of natural aggregates as well as fossil fuels as a result of utilizing the bottom ash favors utilization over landfilling. Utilization does slightly affect the available groundwater resources. However, according to the study, the environmental impact of leaching of sodium- and chloride ions shows an environmental impact of 7 and 3%, respectively, compared to the impact following salting of icy roads, which for example is done in Denmark (Birgisdóttir, Bhander, Hauschild, & Christensen, 2007).

The grain size distribution curve, as presented in Figure 21, influences the permeability and thus the leaching rate. If the fine fraction of the bottom ash is sieved from the mixture, water will pass through the bottom ash layer more easily. The grain size distribution curve thus also play a role for the practical leaching from bottom ash. Furthermore, by choosing to use bottom ashes in areas with an already low permeability, environmental concerns are brought to a minimum.
There is a global trend to move away from a linear economy, where used biogenic and non-biogenic matter are disposed of, towards a circular economy, where efforts are made to re-introduce this matter back into society. By re-introducing the matter to the economy, the demand for virgin matter is lowered, thus lowering the overall resource consumption and ecological footprint.

Wastes which are not eligible for reuse or recycling should be sent for incineration with energy recovery, as opposed to being lost in landfilling. The energy recovery from incineration will, just as any recycled material, be re-introduced to society. The produced energy will offset another source of fuel, e.g. fossil or nuclear fuels. Hence, energy recovery from waste incineration causes a decrease in demand for fossil fuels.

Furthermore, the mineral fraction can, as described earlier, be utilized substituting virgin gravel material. Also, metals recovered from the bottom ash are primarily arise from a composite material, e.g. nails in wood, zippers from clothing, copper wire bits, stainless steel ball pen tips and gold soldering in electronic circuit boards. These metals are also recycled, causing a decrease in demand for virgin metal mining.

Figure 25 depicts the concept of circular economy, with incinerations contribution with energy recovery and utilization of minerals and recycling of metals included.

As Figure 25 also depicts, an important benefit of waste-to-energy is that hazardous components in the waste are isolated from the biosphere, instead of being reintroduced in new products or foods. This benefit is due to the highly efficient flue gas cleaning systems seen in modern Waste-to-Energy facilities.
With all the incineration plants in operation and being implemented worldwide, it becomes increasingly important to use circular economy thinking when seeking to increase the environmental performance of incineration.

The AFATEK facility in Copenhagen has experienced an increased separation of metals from bottom ash, and expects an increase with their new facility planned to be put into operation in 2015. Figure 26 depicts the separated iron and non-ferrous metal from 600,000 tonne of bottom ash. Figure 27 depicts the total metal separation and corresponding value using 2014 secondary metal prices.

The recent and expected future increase in recovery of ferrous and non-ferrous metals are primarily due to the ability to effectively sort the fine fractions of the bottom ash. Not only does this increase the amount of metals sorted for recycling, the fine fraction of bottom ash has a high occurrence of very valuable metals such as gold and silver. The future abilities depicted in Figure 27 are based on the goal to sort down to 0.5 mm.

Roughly 450 incineration plants exist in Europe, recovering the energy of nearly 70 million tonne of waste per year. This corresponds to a total of approximately 16 million tonne of bottom ash per year. Using the metal content and prices as

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**Figure 26** Recovered metals from bottom ash in Denmark. From treatment of 600,000 tonne/year.

**Figure 27** Previous, current and estimated future amount and value of metals recovered from the Danish bottom ash sorting plant, AFATEK.
presented in **Figure 26** and **Figure 27**, the total metal value in bottom ash from all incinerators in Europe could very well reach beyond 550 million € per year. Thus, a valuable market in continuing the technical development and expanding the recovery of metals from bottom ashes exists.

As described in section 6, bottom ash has shown to be well suited as a fill material in construction such as road construction and highway embankments etc. Furthermore, other uses are being investigated. An example of other use is in low tensile strength concrete products, such as outdoor tiles. The use of concrete products in modern society is quite substantial; hence, large markets for bottom ash utilization may exist.

Due to bottom ash being the most significant product from incineration (in terms of mass) utilization is an important element in circular economy.
8 MARKET TRENDS

The market for separation of metals from bottom ashes has shown great developments during recent years. The recovery equipment has become more advanced and efficient, as has the knowledge regarding the importance of precise fractioning, monitoring moisture content etc.

The development in recent years, as well as the expected development in the near future, have and will primarily be due to the ability to sort the very fine fractions of the bottom ash. Additionally, a wider range of valuable metals is being recovered. Experience has shown that sorting on the very fine fractions has great value, as very valuable metals are present in the fine fraction, e.g. gold from soldering on circuit boards. Although metal prices are subject to short-term variation, the long term trend has historically been increasing. Metal prices are therefore expected to continue to rise. Consequently, the economic importance of metal recovery is expected to increase over time.

In relation to the widespread political trend of increased focus on resource recovery, it is important to recover as many metals as possible. Separate collection schemes usually focus on larger objects such as aluminum cans, tin cans and cutlery. However, metal will still indeed be present in the residual waste, as a significant amount of the metal recovered in bottom ash treatment arise from composite materials or of very little dimensions.

Metals in the residual waste can be recovered by mechanical sorting prior to incineration. Mechanical sorting involves shredding and the same type of sorting technology as described in section 5. Such sorting plants face the challenge of dealing with a very inhomogeneous stream of materials. The incineration process is a cheap and effective way to homogenize this stream of material making sorting for metals easier (as all organic material is combusted during incineration). Furthermore, the incineration process will produce energy, whereas a presorting plant will consume energy.

As flue gas cleaning technology has become very effective, it is environmentally sound to incinerate fractions such as automotive shredder residue (ASR), as opposed to landfilling such fractions. ASR has a high calorific value and relatively high metal content. Consequently, re-routing such waste fractions from landfills to incinerators will benefit in terms of energy and metal recycling. However, consideration has to be given to the operation of the plant as well as potential increased dust build-up in the convective part of the boiler.

Bottom ash upgrading is around Europe being carried out in various ways. Different technical setups are seen as well as organizational difference. Centralized sorting plants owned by multiple incinerators are common, avoiding the need for individual investments and exploiting economy of scale affects. Some plants have their own bottom ash treatment plant installed as an integral part of their process. Examples hereof are Emmenspitz in Switzerland and SYSAV in Sweden.

Contractors supplying sorting equipment and personnel are also commonly seen in Europe. Such contractors operate in agreement of a treatment price per tonne of bottom ash treated. Some companies even claim to operate as a net payer, following the high income generated by metal recycling.
The barriers for utilization of bottom ash in construction, such as in road construction, are very much tied to the general barriers for incineration. Although more than 1000 WtE facilities exist worldwide in more than 40 countries, incineration only account for roughly 10% of global municipal solid waste processing. The remaining waste is primarily landfilled, in which neither the energy nor materials are utilized. The lacking WtE capacity is believed to, primarily, be due to an outdated and negative perception of the environmental impact of incineration technology. Modern incinerators that conform to the European Union’s Waste Incineration Directives emission standards, DIRECTIVE 2000/76/EC, bring positive environmental gains as opposed to alternative landfilling of waste (Davidson, 2014). Furthermore, with regard to emissions, such incinerators are able to perform favourably compared to coal power plants (Institut for Miljøvidenskab, 2013).

Dialog with the public and government bodies is crucial to succeed with incineration as well as bottom ash utilization. As described in section 6, bottom ash as such can be an excellent building material that shows an acceptable environmental impact. Furthermore, making use of bottom ash shows resource savings in virgin materials and fossil fuels.

The environmental cost of extracting metals from bottom ash is almost negligible, when compared to the environmental gain of recycling. Furthermore, extracting metals improves mechanical properties of the bottom ash and is of increasing economic importance. Regardless if the bottom ash is landfilled or utilized, metal sorting should always be carried out.

A general perception that metals are destroyed during the incineration exists. While the loss of some metals in the incineration process does occur, the amount is miniscule compared to that made available by liberating the metals from the surrounding organic material. Liberation, that comes with an energy benefit, as opposed to a cost if liberated mechanically (shredding/crushing of the waste).

Energy efficiency of a WtE plant is in the European Union defined by the R1 formula. Expansion of such formula to include bottom ash utilization and metal sorting would increase focus on this great resource conservation opportunity and spur development even further.

9 BARRIERS FOR BOTTOM ASH UTILIZATION AND METAL SORTING
10 WORKS CITED


### ESTIMATED CONCENTRATION OF GOLD AND SILVER IN BOTTOM ASH

<table>
<thead>
<tr>
<th></th>
<th>Bottom ash &gt; 5 mm</th>
<th>Non-ferrous metal fraction &lt; 5 mm</th>
<th>Ferrous metal fraction &lt; 5 mm</th>
<th>Treated bottom ash &lt; 5 mm</th>
<th>Micro-bottom ash &lt; 0.7 mm</th>
<th>Boiler ash</th>
<th>ESP-ash</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silver</strong></td>
<td>0.41</td>
<td>0.094</td>
<td>0.02</td>
<td>0.064</td>
<td>0.162</td>
<td>0.033</td>
<td>0.218</td>
</tr>
<tr>
<td><strong>Gold</strong></td>
<td>0.719</td>
<td>0.066</td>
<td>0.019</td>
<td>0.071</td>
<td>0.078</td>
<td>0.004</td>
<td>0.044</td>
</tr>
</tbody>
</table>

- From (Morf, et al., 2013) Table 3, the concentration of gold and silver in bottom ash is found to be.
- According to (Morf, et al., 2013) Table 5, the distribution of gold and silver to bottom ashes and boiler/ESP ash is found to be.
- Summarized, the distribution to all bottom ash fractions are (sum of first 5 columns above).
- Combining the concentration in waste and the distribution to all bottom ash fractions, the estimated value of gold and silver in bottom ash per kg waste treated is found to be.
- Assuming that one kg waste generates 0.2 kg of bottom ash, the concentration of gold and silver in bottom ash is found to be.

#### Average value in waste (mg/kg waste)

- Silver: 5.3
- Gold: 0.4

#### To all bottom ash fractions

- Silver: 0.75
- Gold: 0.953

#### To bottom ash (mg/kg waste)

- Silver: 3.975
- Gold: 0.3812

#### Concentration in bottom ash (mg/kg)

- Silver: 19.875
- Gold: 1.906